Chester Morse Lake - Spawning Impedance Study
Final Report

Prepared For:

Seattle Public Utilities

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EXECUTIVE SUMMARY

Seattle Public Utilities (SPU) is pursuing a series of studies to understand the environmental effects of tapping "dead storage" in Chester Morse Lake reservoir. This report documents a subset of these studies undertaken by Northwest Hydraulic Consultants (**nhc**) to investigate the changes in reservoir level regime, stream hydraulics, sediment transport, and channel morphology associated with such a project. The objective of this investigation is to advance SPU's understanding of potential impacts of these hydro-geomorphic changes on habitat, fish passage, and water quality with the corollary objective of mitigating or avoiding adverse impacts through tailoring of project design and implementation.

To meet these objectives, **nhc** applied a range of methods and completed a series of tasks summarized as follows:

1. Collected and reviewed available Seattle watershed reports, topographic and survey data, and performed statistical analyses of historical Cedar and Rex river daily discharges as well as Morse Lake levels to characterize baseline conditions that control existing delta and channel morphology.
2. Performed focused field surveys to map the approximate regions of the river channels and deltas that are dominated by silt, sand, and gravel-sized substrate.
3. Statistically analyzed 70 years of "with project" daily reservoir levels simulated by SPU's SEAFM model to characterize the altered reservoir elevation regime, estimate annual probabilities and average durations of river discharges and reservoir levels combinations.
4. Used cross-section and profile data to develop HEC-RAS hydraulic models of the near-delta and delta reaches of the Cedar and the Rex and applied these models to estimate sediment rating curves for each river's gravel and fine (sand and silt) bed materials.
5. Applied channel regime theory to estimate the cross-sections and profile of silt, sand, and gravel reaches of both rivers that represent a quasi-equilibrium "endpoint" of erosion processes following deep drawdowns associated with the "with project" reservoir regime.
6. Compared regime-based "endpoint" morphology with existing morphology to estimate the volume of silt, sand, and gravel that must be mobilized and eroded to establish regime conditions.
7. Applied sediment rating curves with sediment volumes to synthesize curves depicting elapsed time to reach "endpoint" erosion volumes as a function of Cedar and Rex river discharges.
8. Applied "with project" statistical analysis of discharges and reservoir levels to provide guidance on the range of time periods required to establish these "endpoint" Cedar and Rex river delta channel morphologies following "dead storage" project implementation as assumed in the "with project" scenario.
9. Utilized endpoint channel and profile characteristics predicted by the sediment transport analysis and regime theory in the HEC-RAS hydraulic model to develop a comparison between existing and endpoint flow depths and velocities within the Cedar and Rex river study reaches over a wide range of foreseeable discharges.

Key findings from the study components listed above summarized below.

Existing Substrate and Profile of Delta Channels

Pre-existing datasets augmented by project sampling show that the Cedar River delta channel discharges over a steep (9% slope) mud face (foreset). Upstream of the brink the channel has a slope of approximately 0.10% and continues to be dominated by mud for approximately 2,000 ft. Moving in an upstream direction the bed becomes dominated by sandy sediments for approximately 3,000 ft which then gives way to a gravel-dominated channel with a gradient of approximately 0.4%. The study area included approximately 5,000 ft of gravel bedded stream channel. Morphology and composition of the Rex River delta differs significantly from the Cedar River delta in that the mud reach on the Rex is very short and quickly gives way to somewhat steeper and longer sand reach followed by a gravel reach of similar length and gradient to the Cedar.

Historical Reservoir Levels and River Flow Patterns

The surface (topset) of the existing Cedar and Rex river deltas stands at an elevation of approximately 1,538 ft. Since at least the mid-1940s and probably before, water has inundated the delta topsets approximately 98% of the time and deltas have only rarely (5% of the time) during the months of September through November during more severe drought years. During extreme droughts, the lowest reservoir levels have occurred in October and November when there has been a 1% chance of reaching a low extreme of 1,532 ft.

Under typical (median) conditions, Rex and Cedar river flows into the reservoir exhibit a double peak seasonal pattern characteristic of rain and snow dominated Cascade watershed with the primary volume peak occurring in May and the secondary volume peak occurring during November or December as a result of winter storms. Late autumn and early winter rain storms combined with snow melt generate the highest, short-duration, peak discharges on both rivers.

"With Project" Reservoir Level Regime

Aggressive operation of a pumping plant for the purpose of maximizing water withdrawals at the limit set by the Seattle-MIT agreement and meeting HCP normal instream flows, results in deep and sometimes protracted drawdowns of the lake below the existing delta topsets approximately one year in three. These large drawdowns typically occur in the fall to early winter, but in extreme droughts such as the one that occurred in water year 1941, the drawdown may persist into mid-winter. The 95% exceedance line which under historical conditions roughly equaled the 1,537-1,538 ft elevation of the existing delta topsets during the months of September and October, would drop to approximately the 1,518 ft level under the "with project" scenario while reservoir levels during the spring would typically be equal to or higher than historical conditions. Thus the dynamic range of Morse Lake reservoir elevations would effectively increase by approximately 20-25 ft.

Channel Adjustments at Erosion Endpoint Under "With Project" Operations

Delta foreset crests are likely to drop to approximately the 1,517-1,518 ft level under "with project" conditions. This expectation is based on the erodibility of the fine delta sediments in the lowest reaches of the Rex and Cedar channels as well as on the rough equivalence in frequency between the existing 1,537-1,538 ft elevation range and the "with project" 1,517-1,518 ft elevation range. Based on bed slopes, bottom widths, and side slopes indicated by regime theory, the volume of erosion to reach quasi-equilibrium on the Rex and Cedar Rivers was estimated to be 340,000 and 930,000 cubic yards respectively.

The actual amount of time it would take to erode this amount of material and re-equilibrate these channels would depend primarily on the range of flows that the adjusting Cedar and Rex river channels would be subjected to as well as whether or not reservoir levels are high enough at the time of a given discharge to impose backwater conditions that reduce velocities and transport capacity. Based on the hydrologic statistics, it is expected that finer sand and mud material would generally be "excavated" by flows in both rivers during the initial autumn in which the first significant drawdown occurs. Equilibration of gravel-dominated channels would be expected to occur within 5 years following implementation of a pumping project.

Comparison of Existing and "With Project" Stream Velocities and Depths

The HEC-RAS hydraulic model was used to investigate the velocity and depth profiles through the delta channel and upstream gravel reach of each river over a range of discharges up to a 2-year peak flow. While there are some local differences in velocities and depths at specific stations, on average, model results show that existing and "endpoint" hydraulic conditions are quite similar.

Reservoir Turbidity Following Project Implementation

The downstream portions of the Cedar and Rex deltas is composed of highly erodible and mobile mud materials that are in the silt sediment size range. Based on the field data collected in this study, the upstream extent of this mud material is more extensive on the Cedar River than on the Rex River. The initial lowering of the reservoir results in high speed flow down the extremely steep delta foresets that is certain to cause rapid erosion of delta muds and resultant reservoir turbidity. Without specific mitigation, turbidity is likely to persist until stable bed and bank slopes are established in the delta channels.

Recommendations

1. Managed Reservoir Drawdown- SPU should consider controlling the rate and timing of the channel adjustment process to minimize impacts on fish migration and water supply. This could include creating a temporary, artificial drawdown during a period

when water demands are low and alternate sources are adequate. This technique can also be used to avoid an extreme initial drawdown during a drought which increases the risk of fish passage problems if freshets are overly late.

2. Limited Test Drawdown- Similar in character to Managed Reservoir Drawdown, a Test Drawdown would be implemented during a low-risk period for fish and water supply in order to observe the rate and character of channel adjustments as well as the intensity and duration of turbidity caused by lowering a modest distance below the topset elevation.

3. Further Simulation and Field Studies
    a. Dynamic Sediment and Monte Carlo Modeling- The geomorphological scope of this study was limited to first approximations of endpoint channel adjustments resulting from erosion associated with a single, aggressive "dead storage" access scenario. As such, neither the variable response of the deltas and channels to different "dead storage" implementation strategies, nor the timing and probability of channel and delta adjustment pathways and their resultant variable impacts on fish and water supply could be addressed in any detail. Application of a dynamic sediment transport model would provide a much more detailed and accurate picture of channel evolution resulting from different "dead storage" access scenarios. Such a model could be run multiple times using different historical and hypothetical sequences of inflows to help identify the frequency and range of channel and delta morphology trajectories. Dynamic modeling would also provide a more highly resolved assessment of timing, frequency, intensity, and duration of turbidity events, and potentially provide insights into the progradation of the eroded deltas into the reservoir.

    b. Additional Data Collection- the more detailed modeling recommended above would be greatly enhanced by gathering additional field data to characterize the stratigraphy of the existing deltas. This could be accomplished using several alternative methods including non-intrusive subsurface geophysical survey techniques.

1.0 INTRODUCTION

1.1 Project Objectives and Background

The objective of this study is to assess the potential effects of various Seattle Public Utilities (SPU) reservoir "dead storage" operational scenarios (or natural events) on geomorphic processes occurring in both riverine and lacustrine environs of the Cedar and Rex river deltas, near the area of confluence with Chester Morse Lake reservoir, particularly in regard to the potential for these effects to impede the annual fall spawning migration of adfluvial bull trout or pygmy whitefish.

SPU has proposed the Cedar Permanent Dead Storage Project as a possible operational means by which to gain access/utilize the reservoir's currently unrealized additional yield retained in dead storage (below current drawdown levels). In so doing, however, any method of water withdrawal would necessarily require that the reservoir's water surface be drawn down periodically to elevations not typically reached under current reservoir fill and drawdown regimes (except occasional periods of drought). Such use of dead storage (i.e., drawdown) would therefore periodically expose reaches of Cedar and Rex river substrates and existing delta deposits to a greater extent, and over periods of variable duration, than is typical under current operating regimes.

1.2 Project Authority and Acknowledgements

This project was authorized by the Seattle Public Utilities through contract number R00-80-06-03 with Northwest Hydraulic Consultants Inc. (**nhc**), dated 1 March 2006. The contract was initially managed by Mr. Dan Basketfield at SPU during project startup and initial implementation, and then managed by Mr. Tom Fox through project completion. Project data was provided by several individuals at SPU, including Mr. Mike Lynch, Ms. Moya Joubert, Mr. Dave Beedle, Mr. Mark Joselyn, and Ms. Katie Saylor. Project operational data for existing and proposed drawdown operation conditions was provided by Mr. Tom Johanson. Site and field measurement access at Chester Morse Lake (CML) was coordinated by Mr. Dwayne Paige. The assistance of all these individuals is gratefully acknowledged.

2.0 SITE UNDERSTANDING

2.1 Watershed Characteristics

Chester Morse Lake reservoir is located in eastern King County approximately 30 miles southeast of the City of Seattle, Washington. Following the construction of the Timber Crib Dam (i.e., Crib Dam) in the early 1900's, now called the Overflow Dike after replacement in 1988, the reservoir became the primary municipal water supply for the City of Seattle, as well as providing hydroelectric power to the City. Prior to the construction of the Crib Dam circa 1904, Chester Morse Lake reservoir was a natural water body commonly referred to as Cedar Lake. Subsequent construction of the Masonry Dam circa 1915, creating the Masonry Pool, augmented storage capacity of the reservoir complex, provided increased capacity to generate hydroelectric power, and allowed limited flood control on the lower Cedar River.

The watershed upstream of Masonry Dam has a drainage area of approximately 83 sq. miles. Eight (8) small creeks drain into the reservoir complex; however, the Cedar and Rex Rivers are the two largest tributaries with contributing drainage basin areas of approximately 41 and 22 sq. mi., respectively. A detailed description of basin characteristics is provided in Section 3.1.

2.2 Watershed History

Cedar Lake has existed since the last glaciation of the Puget Sound lowlands. During the glacial maximum, approximately 14,000 years ago, the lake was impounded by the Cascade Mountains to the east, and the Puget Lobe of the Cordilleran icesheet to the west (Hong, 1988). Once the glaciers began to recede the lake was maintained by a glacial moraine deposit composed of alluvium. It has been estimated that lake water surface elevations have dropped approximately 30 to 50 ft since the glacial maximum, as the Cedar River eroded through the moraine embankment (Hirsch, 1975). The moraine deposit is still present adjacent to the Masonry Dam and prevents the Cedar River from draining into the Snoqualmie basin to the north (Hirsch, 1975).

Logging activities around Cedar Lake started in the late 1800's and continued until 1996 when the City of Seattle took sole ownership of the watershed. Prior to 1924, poor forestry management practices and frequent fires made replanting efforts difficult and ineffective. Soon thereafter the City hired their first forester on a permanent basis, which lead to improved logging practices and fire protection.

Transformation of Cedar Lake into the Chester Morse Lake reservoir began in 1903-1904, with the construction of the Timber Crib Dam. Located near the natural bedrock outlet to the lake, the Timber Crib Dam raised water surface elevations approximately 17 ft, from a natural lake elevation of 1,530 ft. Construction of the Masonry Dam, located about a mile downstream of the Timber Crib Dam, was completed in 1914 with an "operating" crest elevation of 1,561.5 ft (McWilliams, 1955). The Masonry Dam was planned to provide storage up to an elevation of 1,590 ft, but seepage through the adjacent moraine and associated safety risks made this unfeasible (SWD 1986). The aging Crib Dam was replaced in 1988 by the construction of the Overflow Dike located just downstream.

2.3 Bathymetric and Topographic Surveys

2.3.1 Recent Data

In 2005, SPU survey crews completed bathymetric surveys of the submerged portions of the Cedar and Rex deltas. Ground surveys of the respective channels upstream of the deltas were also conducted. The channel surveys extended approximately 3.3 miles upstream to the Camp 18 Bridge on the Cedar River, and 1.9 miles upstream on the Rex River. Surveys of the channels were generally contained within the banks, although some floodplain points were also collected. Ground surveys were also conducted around the deltas and adjacent shore of the lake..

The combined bathymetric and ground survey data were obtained in point format from SPU and later used to create a triangulated irregular network (TIN) surface of the Cedar and Rex deltas. The survey extents and TIN surfaces of the Cedar and Rex study reaches are shown in Figures 5a–b. The data were later used in the construction of a hydraulic model, as discussed in Section 4.2.1.

2.3.2 Historic Data

Historic maps showing topography and limited bathymetry, as well as historic aerial photos, were obtained from the SPU Cedar River Watershed Education Center. Topographic data, consisting of 5-ft interval contours, was surveyed prior to 1913, and likely collected by the U.S. Coast and Geologic Survey; however, no formal source information was provided on the maps. Bathymetric data were collected by the City of Seattle in 1915, and the aerial photos were flown in the early 1930's. Figures of the historic maps and aerials are included in Appendix A, while a discussion of the analysis performed using the historic data is given in Section 4.1.2.

2.3.3 Vertical Datum

The elevations of the various terrain data obtained by **nhc**, both current and historic, were reported in different vertical datums (e.g., NAVD 1988, NGVD 1929, Mean Sea Level, etc…). To be consistent, **nhc** converted all data received, when possible, to the City of Seattle Vertical Datum (SVD). During this process, however, a discrepancy between the City's datum within the city limits and at Chester Morse reservoir was discovered. A discussion of this discrepancy and its origin is given in Appendix B.

As a result of the difference between City datums, they are distinguished as SVD in the city limits and SVD_{CM} at the Chester Morse Lake reservoir. **All elevations converted and reported in this study are SVD_{CM}.**

2.4 Effects of Reservoir Drawdown – Dam Removal Analogy

Numerous dam removal studies have been conducted in the recent past. Methods of analysis range from analytic and numerical models to laboratory and field scale experiments. During these studies, two scenarios are often evaluated: rapid removal of a dam and subsequent rapid drawdown, or a controlled, staged drawdown. The revised operations proposed for Chester Morse Lake reservoir are more similar in character to the latter. One field study that is particularly relevant to the proposed operations at Chester Morse Lake reservoir is discussed below.

2.4.1 Glines Canyon, Elwha River, Washington

In spring 1994, a reservoir drawdown experiment was conducted at Lake Mills on the Olympic Peninsula, Washington. Lake Mills is a reservoir created by the Glines Canyon Dam, which was completed in 1927, on the Elwha River (USGS, 2000). The purpose of this project was to evaluate sediment transport characteristics and geomorphic effects of the proposed removal of both the Glines Canyon and Elwha Dams.

The project consisted of a controlled lowering of the lake by 18 ft over a week-long period, followed by another week of the lake being held at a constant elevation. During this two-week period, channel surveys were performed and sediment transport rates measured. Daily discharges measured upstream of the delta ranged from 890 to 1,760 cfs. Downstream of the dam, daily discharges ranged from 1,100 to 2,090 cfs and were estimated to be equaled or exceeded 56% and 20% of the time on average, respectively. Furthermore, the 2-year recurrence interval discharge downstream of the site was estimated as 13,000 cfs (USGS, 2000).

During the first week, the vertical channel adjustments occurred at the same rate as drawdown. Once the reservoir reached a constant elevation, lateral cross-sectional adjustments occurred with rates of lateral bank migration of up to 80 ft/hr.

Based on channel surveys, it was estimated that over 300,000 cubic yards of sediment was eroded from the delta during the two week period, with much of it transported immediately downstream to form a new delta deposit. Increased turbidity was observed within Lake Mills; however, it was speculated that much of this material settled within the lake as only small increases of suspended sediment were measured downstream of the dam (USGS, 2000).

3.0 STREAM FLOWS AND RESERVOIR LEVELS UNDER HISTORICAL AND "WITH-PROJECT" CONDITIONS

This section is divided into two sub-sections; the first characterizes existing hydrologic conditions including a summary of stream basin characteristics and flow regimes for the upper Cedar and Rex Rivers as well as the historical stage fluctuations of Chester Morse Lake reservoir. This characterization of flow regime is based on USGS daily stream flow and reservoir level data. The stream basin characteristics, stream flow regimes, and reservoir operations represent key determinants of the existing geomorphology of the Cedar and Rex river deltas and their respective channels.

The second sub-section describes a potential future "with project" condition as simulated using the SPU SEAFM watershed, reservoir, and stream flow model. The model was used to simulate 70 years of daily flow and reservoir levels assuming the existence of a pumping plant that accesses "dead storage", to satisfy normal instream flow requirements and maximize M&I water diversions at Landsburg consistent with the Cedar River HCP and Seattle-MIT agreement. This scenario was not selected for realism or because it is preferred. Rather, it represents one scenario depicting a relatively aggressive use of current "dead storage" that results in greatly altered reservoir stage regime that in which much deeper drawdowns occur much more frequently. The reservoir level regime from this scenario is contrasted with the historic regime. It is also used to inform the hydraulic and geomorphic analysis that focuses on projected adjustments of the Cedar and Rex river deltas and their channels to this "with project" reservoir regime.

3.1 Basin Characteristics

The Cedar and Rex Rivers are the primary inflow streams to Chester Morse Lake reservoir. They drain adjacent forested basins southeast and south-southeast of the reservoir. Drainage areas of the basins are approximately 41 and 22 sq. mi., respectively. Although both basin stream networks terminate in low gradient channels that traverse their respective deltas at the reservoir, the stream networks as a whole are dominated by moderate to steep gradients, with step-pool structure characteristic of Cascade mountain forest streams. The upper Cedar River rises from Chester Morse Lake reservoir at an approximate elevation of 1,550 ft to the Cascade crest at the tops of several peaks including Mount Baldy (el. 5,200 ft), Abiel Peak (el. 5,365 ft), Tinkham Peak (el. 5,395 ft), and Goat Mountain (el. 4,773 ft). While the high points of the Rex River basin are generally 1,000 ft lower than the Cedar, the Rex basin's relief ration is approximately 6% compared to approximately 3% for the Cedar, because of a much shorter distance from the mouth of the Rex to its basin crest. Below elevations of approximately 1,600 ft the surface geology generally consists of porous glacial deposits and alluvium and above 1,600 ft the geology transitions from alluvium to bedrock. Median forest stand age is in excess of 65 years in both basins and each is dominated by closed-canopy forest, including mid-seral (age 40-79 years), and mature trees (age 80-119 years). The basins receive average annual precipitation of approximately 120 inches, more than half of which typically falls as snow.

3.2 Flow Characteristics

Multi-decade discharge records from USGS gage 12115000 on the Cedar River at Camp 18 and 12115500 on the Rex River are available to characterize seasonal pattern and flood characteristics of the streams. The seasonal patterns of flow on the two streams are essentially similar with annual hydrographs exhibiting a double peak that is typical of streams influenced both by rain storms and snow melt. On an annual basis, flows rise from their lowest levels at summer's end as autumn rains begin. Winter flows often reflect a combination of runoff from rainfall that is augmented by snowmelt episodes when warm air accompanies frontal storms (so-called "Pineapple Express" events) originating in the south Pacific. The highest mean daily flows of the year typically occur in May as a result of seasonal snowmelt augmented by spring rain storms. During the low flow period, typically between July and October, mean daily flows range from approximately 50 to 100 cfs, and 10 to 50 cfs, at the Cedar and Rex River USGS gages, respectively.

Table 1 presents annual flood frequency curves for both the upper Cedar and Rex Rivers. On a unit area basis, the Rex River is clearly the "flashier" of the two streams, as is typically the case when comparing a smaller to a larger drainage basin.

Table 1. Instantaneous Peak Annual Flood Frequency Curves, Log-Pearson III, Bulletin 17B, WRC

Annual Probability of Exceedance	Average Recurrence Interval (years)	Cedar River at USGS 12115000, DA=40.5 sq mi (cfs)	Rex River at USGS 12115500, DA=13.4 sq mi (cfs)
99%	1.01	648	414
50%	2	2,797	1,659
20%	5	4,296	2,492
10%	10	5,272	3,027
4%	25	6,466	3,673
2%	50	7,319	4,131
1%	100	8,142	4,571

3.3 Historical Incidence of Low Chester Morse Lake Levels

An analysis of historical daily Chester Morse Lake reservoir elevations was undertaken to determine fluctuation in the depth of water covering the Cedar and Rex river delta topsets and the historical probability of topset exposure. Typically (based on median monthly water surface elevations), reservoir levels have varied from a low of 1,544 ft in September to a high of 1,557 ft in May and June. As might be expected, given the existence of apparently stable delta topsets with brink elevations between 1,537 and 1,538 ft, the topsets are typically submerged under several feet of water throughout the years and exposure of the brinks occurs perhaps once in five years (20% chance of annual water surface drop) between September and November. Consistent with drought conditions that accompany these infrequent low reservoir levels, Cedar and Rex river discharges are less than half their respective mean annual discharges 95% of the time. Delta topset exposure, therefore, is infrequent and flow erosivity during exposure is relatively low.

Table 2 indicates the percentage of years in which upper Cedar River inflows to the lake exceed specified levels concurrently with reservior levels less than specified levels. Table 3 represents the average duration of the joint low elevation and discharge exceedance events for years when the joint condition is met. These results are for the Cedar River and delta. Rex River results are similar and are provided in Appendix C.

Table 2. Percent of Years with Daily Q Higher and Chester Morse Lake Elevations Lower, Historical Conditions

Reservoir Elevations, ft above SVD_{cm}	Cedar River Discharge Exceedance Levels (cfs)					
	>0	>50	>100	>200	>400	>600
<1,545	93.2%	89.8%	74.6%	47.5%	23.7%	10.2%
<1,540	40.7%	40.7%	23.7%	11.9%	1.7%[1]	0.0%
<1,538	25.4%	20.3%	15.3%	5.1%	0.0%	0.0%
<1,536	16.9%	6.8%	3.4%	1.7%[1]	0.0%	0.0%
<1,534	8.5%	1.7%[1]	0.0%	0.0%	0.0%	0.0%
<1,532	1.7%[1]	0.0%	0.0%	0.0%	0.0%	0.0%
<1,530	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 3. Average Duration of Joint Discharge Exceedance with Low Chester Morse Lake Elevations, Cedar River (days)

Reservoir Elevations, ft above SVD_{cm}	Cedar River Discharge Exceedance Levels (cfs)					
	>0	>50	>100	>200	>400	>600
<1,545	77.3	46.2	22.4	9.0	2.8	2.2
<1,540	37.4	13.0	8.2	3.0	1.0[1]	0.0
<1,538	33.1	11.8	7.1	4.0	0.0	0.0
<1,536	25.9	14.8	9.0	3.0	0.0	0.0
<1,534	23.4	7.0[1]	0.0	0.0	0.0	0.0
<1,532	54.0[1]	0.0	0.0	0.0	0.0	0.0
<1,530	0.0	0.0	0.0	0.0	0.0	0.0

[1]One event in record from water year 1946 through water year 2004.

Channel forming or erosive flows that determine the cross-sectional properties and equilibrium slope of an alluvial channel are often defined in terms of a stream's peak annual flood frequency curve. Bankfull discharge is found to be well-approximated by the median (2-year or 50% annual exceedance probability) instantaneous peak flow. Channel forming flows are typically identified as ranging between the 1.01-year (99% annual exceedance probability) and 2-year peak flow. *Historically, mean daily flows have almost never occurred without at least several feet of water covering the topsets of both river deltas.*

It should be noted that the forgoing discussion of historical flow and reservoir level regimes represents a selection and summarization of a detailed hydrologic analysis that is documented in Appendix C. This detailed analysis is based on 59 years of historical daily discharge and reservoir level data (water years 1946-2004) and includes:

1. Statistical analysis of the variability of mean daily flow data throughout the year for each stream.
2. Discussion of the onset of autumn freshets and winter storm flows with example hydrographs.
3. Full discussion of the historic fluctuations of Morse Lake elevations including statistical analysis presented as 1% through 99% exceedance probability curves illustrating rare, extreme lows, typical mid-range levels, and rare extreme highs throughout the water year.
4. Statistical analysis of the historical frequency of joint Cedar and Rex river flow exceedances and reservoir levels that expose the existing delta topsets.

All frequency analysis utilized mean daily flow and daily reservoir elevation data. Daily data were grouped by month for purposes of frequency analysis, summarization and plotting; daily data were not averaged.

3.4 Frequency and Duration of Erosive Conditions Under Potential Future "With Project" Operations

In order to characterize changes in delta and stream geomorphology that may occur as a result of a project that enables more routine use of Chester Morse Lake reservior dead storage to meet both municipal water supply and lower Cedar River instream flow requirements, SPU hydrologic modeling staff (personal communication, Tom Johanson, SPU) were requested to carry out long-term simulations of reservoir inflow, storage, and elevation using the Seattle Forecasting Model (SEAFM). SEAFM computes watershed runoff and reservoir inflows from meteorological data, simulates reservoir operations and outflows through low level outlets, power penstocks, and spillways, estimates the behavior of groundwater flow to and from the Cedar moraine, and calculates resultant flows in the lower Cedar River on an hourly basis.

Simulations were carried out for a 70-year period extending from water year 1929 through water year 1999. In these simulations, a Morse Lake reservoir pumping plant was assumed to exist and freely access dead storage down to elevation 1,517 ft in order to maximize water diversions at the limit specified by Seattle-Muckleshoot Indian Tribe agreement and meet the normal high instream flow requirements contained in the Cedar River Watershed HCP. Details of the setup of the SEAFM runs are provided in Appendix C.

3.5 Results and Comparison with Historical Conditions

Figure 1 compares the range of Chester Morse Lake reservoir levels that can be expected throughout the year assuming a pumping plant and pipeline are used to tap reservoir dead storage to meet the demands of normal high instream flow and a 124 mgd average annual diversion with historical lake level conditions. Operation of a pump plant that accesses dead storage can make a potentially dramatic difference in the elevation regime of Chester Morse Lake reservoir. Referring to the 95% exceedance lines, under historical conditions there has been 5% annual chance of exposing the deltas between the months of August and November; however, the depth of exposure has been negligible. By comparison, under the dead storage access scenario, exposures would range from 2 ft to 20 ft over the same season with the average 1 in 20-year frequency. Overall, the risk of some exposure increases by a factor of three, and the annual probability of the lake being 5 ft below the current delta topset brinks increases from about 2% to 40%.

During the spring, the chance of exposing delta topsets has increased from nil under existing conditions to somewhat more than 1% during the month of March, the period when many rainbow trout access the Cedar and Rex Rivers to spawn.

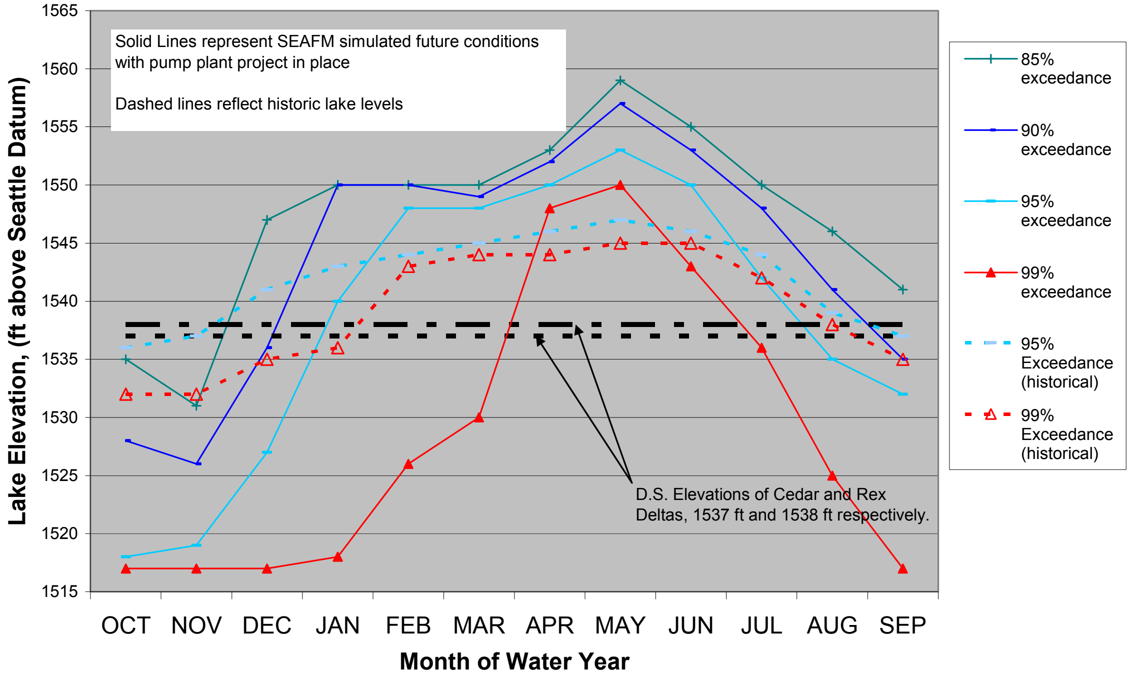


Figure 1. Exceedance Levels of Daily Chester Morse Lake Reservior Elevations by Month.

3.6 Coincidence of High Flows and Low Lake Levels under Potential Future Conditions

Of more significance than the dramatic increase in the probability of lower Chester Morse Lake reservoir levels under the potential future scenario, is the increase in the probability of relatively large stream discharges from either the Rex or the Cedar Rivers coinciding with exposed topsets and partially exposed foresets. Under the proposed scenario, the frequency of topset exposure and the duration of flows during periods of exposure would increase dramatically. Details of these exposure events are shown in Appendix C. There are 29 autumn and early winter events of delta exposure occurring within the 70 year simulation period.

Table 4 and Table 5 compare historical with potential (with project) joint probability and durations for topset erosion events. Again, the results for the Cedar and Rex rivers are similar, thus only those for the Cedar delta are given here. Rex River results are provided in Appendix C. Comparing adjacent values in the tables for incipient topset exposure (el. 1,538 ft), annual probability doubles, and durations >100 cfs go up by nearly a factor of five. For one-two ft of vertical foreset exposure (el. 1,536 ft), probability increases by more than 9 times from 3% to 31% and duration increases by more than a factor of 3 from 9 days to 33 days.

Under potential future conditions drawdown levels below 1,534 ft that virtually never occurred under historical conditions, would be comparatively commonplace occurrences (1 in every 3.5 years on average) during mild autumn or early winter droughts. Discharges in excess of 400 cfs would persist for approximately six days on average. For a more thorough summary of frequency and duration of joint, low elevation and high flow conditions on both deltas, please see Appendix C.

From the perspective of channel adjustment, the key information contained in Table 5 is that under potential future scenarios, mild to severe droughts would cause exposure of delta topsets and foresets that would persist for days, if not weeks. Also, it should be noted that the shorter durations associated with higher flows could be as effective or more effective than the longer durations at lower flows presented in the table.

Table 4. Annual Probability of Daily Cedar Discharge Higher and Chester Morse Lake Reservoir Elevations Lower

Reservoir Elevations, ft above SVD_{cm}	>100 cfs		>200 cfs		>400 cfs	
	Historic	Potential	Historic	Potential	Historic	Potential
<1,545	74.6%	41.8%	47.5%	38.2%	23.7%	34.5%
<1,540	23.7%	36.4%	11.9%	34.5%	1.7%[1]	27.3%
<1,538	15.3%	32.7%	5.1%	30.9%	0.0%	25.5%
<1,536	3.4%	30.9%	1.7%[1]	29.1%	0.0%	25.5%
<1,534	0.0%	29.1%	0.0%	27.3%	0.0%	23.6%
<1,532	0.0%	29.1%	0.0%	27.3%	0.0%	21.8%
<1,530	0.0%	27.3%	0.0%	23.6%	0.0%	21.8%
<1,525	0.0%	21.8%	0.0%	20.0%	0.0%	14.5%
<1,520	0.0%	18.2%	0.0%	16.4%	0.0%	9.1%

Table 5. Average Duration of Joint upper Cedar River Discharge Exceedance with Low Chester Morse Lake Reservoir Elevations (days)

Reservoir Elevations, ft above SVD_{cm}	>100 cfs		>200 cfs		>400 cfs	
	Historic	Potential	Historic	Potential	Historic	Potential
<1,545	22.4	36.5	9.0	22.1	2.8	8.2
<1,540	8.2	33.6	3.0	18.9	1.0	8.0
<1,538	7.1	33.3	4.0	18.7	0.0	7.5
<1,536	9.0	32.8	3.0	17.9	0.0	6.4
<1,534	0.0	31.2	0.0	16.7	0.0	6.1
<1,532	0.0	25.3	0.0	13.7	0.0	5.5
<1,530	0.0	36.5	0.0	12.6	0.0	4.3
<1,525	0.0	17.0	0.0	8.5	0.0	3.3
<1,520	0.0	12.9	0.0	6.0	0.0	1.6

For additional details on the "with project" SEAFM simulation results, including plots of inflow hydrographs and reservoir elevations during years with significant drawdown, please see Appendix C.

4.0 MORPHOLOGIC ANALYSIS

The morphologic analysis employed to evaluate the impacts of the proposed changes in operation of Chester Morse Lake reservoir on the Cedar and Rex river deltas involves several components. First, existing conditions are established. These conditions are defined by the evaluation of historic and recently collected data. Once these initial conditions are defined, the hydraulic conditions of the deltas are evaluated using a numerical model. The results from the numerical model are then coupled with empirical relationships to construct a morphologic model to assess quantities and rates of change expected on the deltas. The following sections discuss these components of the analysis.

4.1 Delta Sedimentation and Stratigraphy

4.1.1 Typical Delta Geometry and Terms

Sediment deposition along a lake/reservoir delta is controlled by the hydraulic conditions and sediment load of the inflowing stream, as well as by the fluctuating water level of the lake/reservoir. Viewed in profile, a lake/reservoir delta is typically divided into three sections; the topset, foreset, and bottomset (see Figure 2). The topset usually consists of coarser material ranging from sand to gravel. Moving downstream, the bed material becomes finer with a transition to sand and silt deposits. Where the fluvial system encounters standing water marks the point of the foreset crest. The foreset is usually formed by a process of avalanching of material as the delta advances lakeward. The bottomset material, usually composed of the finest silt, clay, and organics is deposited either from settling of material from surface plumes or turbidity currents carrying material down the foreset face (Cantelli et al., 2004).

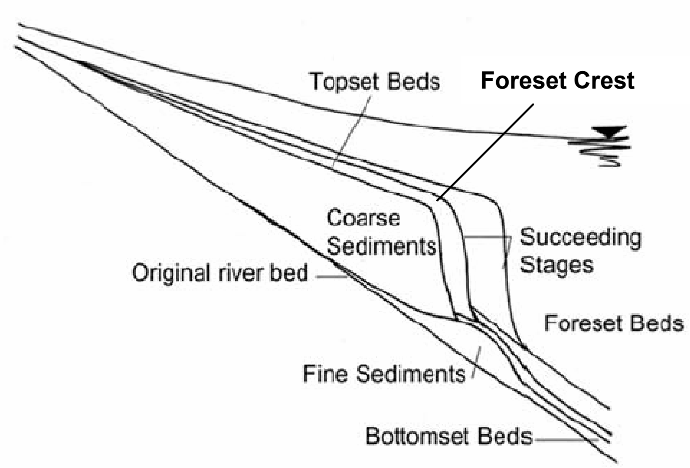


Figure 2. Schematic of typical delta geometry (from Cantelli et al., 2004)

In reservoirs, where substantial water surface fluctuations can occur, delta forms and processes can become more complicated. Significant lowering in water surface elevation may result in erosion of an existing topset and extension of the foreset crest lakeward through subsequent deposition of eroded material. However, under fluctuating conditions that are generally seasonal in length, the long-term, or aggregate, geometry of the delta will still generally resemble those of a static reservoir.

4.1.2 Historic Delta Growth

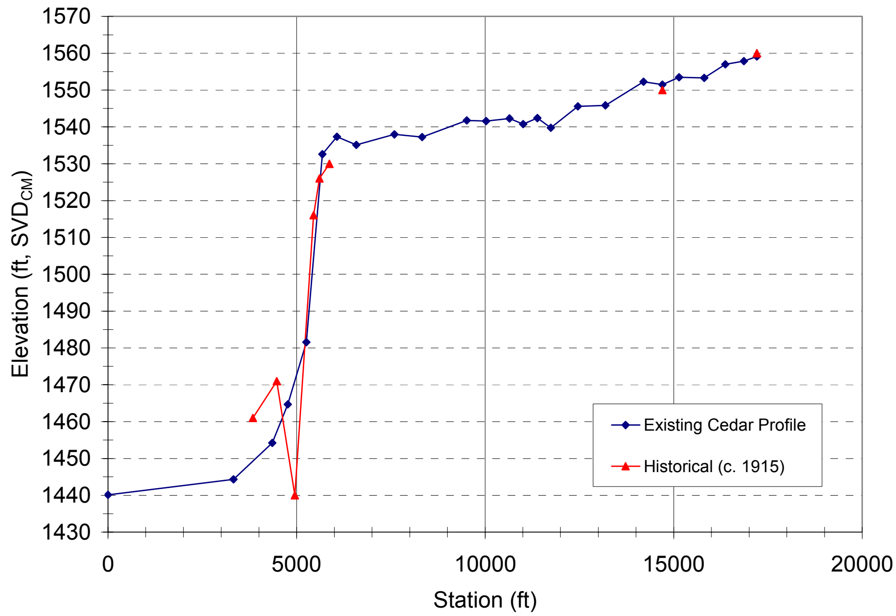
The historic bathymetric data and aerial photos discussed in Section 2.3.1 provide a means of evaluating the expansion of the Cedar and Rex deltas that has occurred over the past 90 years. Delta expansion can be used to gauge the sediment load contributed from the respective watersheds in the recent past, and potentially, what can be expected in the future.

Figure 3a-b presents a comparison between the recently collected bathymetric data and the 1915 historic data. Shown are the longitudinal profiles for existing conditions and estimated point elevations and profiles for historic condition [Note: longitudinal stationing shown in Figure 3a-b, as well as several following figures is based on an arbitrary channel alignment established by **nhc** for this study]. The points delineating the historic foreset crests were given an assumed elevation of 1,530 ft. This was required because the location of these points were obtained from a feature line on the historic maps that appears to indicate the foreset crest location, but does not have an associated elevation such as a contour line would. The value of 1,530 ft was chosen based on the historic Cedar Lake water level, as discussed in Section 2.2. The comparison of the data sets indicates that propagation of the Cedar delta into the lake over the past 90 years has been negligible. On the Rex delta propagation up to 500 ft may have occurred; however, this observation is highly speculative and depends entirely on the assumption made with regard to the historic foreset crest feature line.

Vertical accumulation of sediment over the deltas has likely occurred over the past 90 years, but because of the sparse historic topography it is difficult to estimate a rate or total amount for the period. Upstream of the delta, in the gravel reaches, the historic data indicate that the channels have maintained a similar gradient, but again, it is inconclusive whether the channel has undergone degradation or aggradation.

The observation that upstream gradients have remained similar over the past 90 years, coupled with the observation of limited delta propagation may be evidence that the Cedar and Rex deltas are in a static equilibrium.

It should also be noted that several of the points from the City of Seattle 1915 bathymetric survey (see Section 2.3.2) located near the Cedar bottomset are suspicious and may be erroneous outliers. The source of the error could be from the original survey, or related to datum issues. A vertical datum was not labeled on the historic maps, thus it was assumed that the elevations of the contours and bathymetric points were reported on the Seattle Vertical Datum at Chester Morse Lake reservoir (SVD_{CM}), as discussed in Section 2.3.3. This assumption was made by comparing overlapping historic and current topography in areas where few changes would be expected. It is possible that the datum is Mean Sea Level (MSL), a precursor to NGVD29, but it is difficult to determine with the information available.



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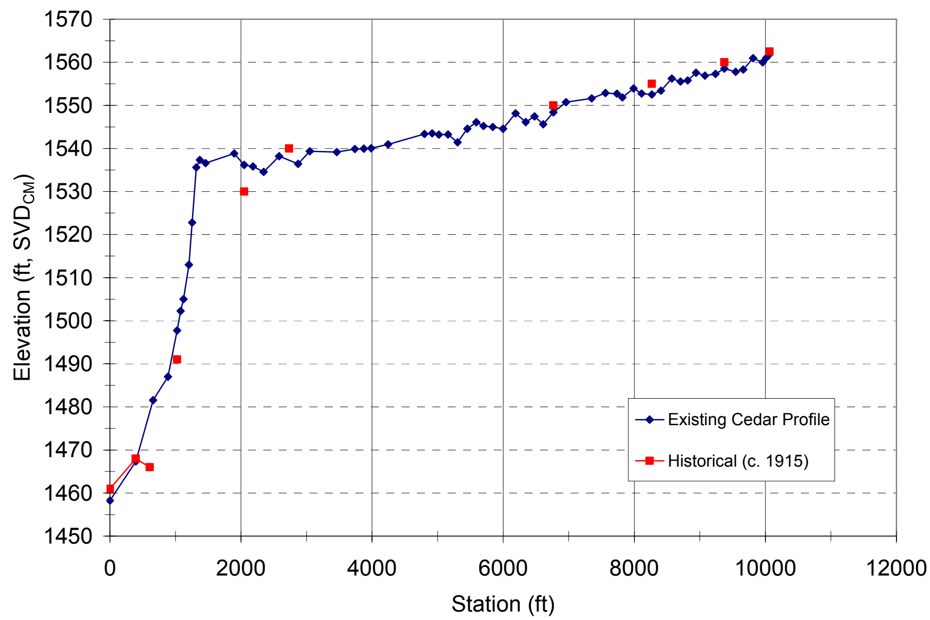


(b)

Figure 3. Historic (City of Seattle, 1915) and existing longitudinal profiles of the Cedar (a) and Rex (b) Rivers.

Historic aerial photographs of the deltas were also used to visually assess expansion of the delta, as well as surface morphology. As discussed in Section 2.2, historic aerial photos from the early 1930's were obtained and compared with those from 2002. A visual comparison of the aerial photos presented in Appendix A shows that the channel planform in the deltas has changed little in approximately 70 years. Slight changes in meander planform are apparent, but because the delta topset is typically inundated much of the year it is probably not geomorphically active.

Inundation levels make it difficult to estimate the location of the delta foresets in the aerials; however, deposits in shallow water can be seen extending lakeward in the 1930 photos to the approximate location of the existing foreset. This would indicate little delta expansion has occurred and would also be consistent with the findings from the historic bathymetric data discussed above.

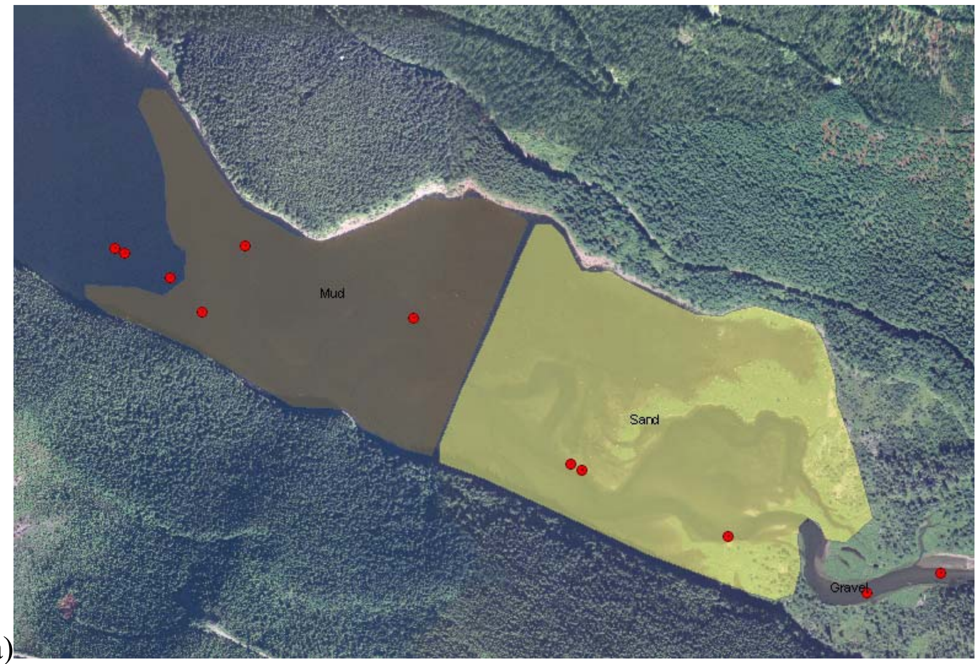
4.1.3 Sediment Load

Sediment budgets are generally computed from sediment discharge measurements or morphometric analysis of sediment deposits. Sediment discharge measurements have not been measured on the two river channels entering Chester Morse Lake reservoir, so a sediment budget cannot be determined from measured data. In addition, differences in channel profiles or delta expansion through aggradational processes could not be accurately determined by comparing historic and current channel surveys with aerial evidence of delta adjustment, as presented in the previous section. A sediment budget, therefore, cannot be determined from the available data; however, it may be presumed that current sediment loads on the Cedar and Rex are relatively low. This is consistent with the tendency for mountain basins to be generally sediment limited, i.e. the competence of the flow to transport sediment exceeds the available supply. Most material is delivered to the channels during infrequent and sporadic mass wasting events rather than continuous bank erosion and bar deposition. Of the two rivers, the Cedar was observed to exhibit more frequent bank sloughing of its more expansive alluvial floodplain immediately upstream of the lake.

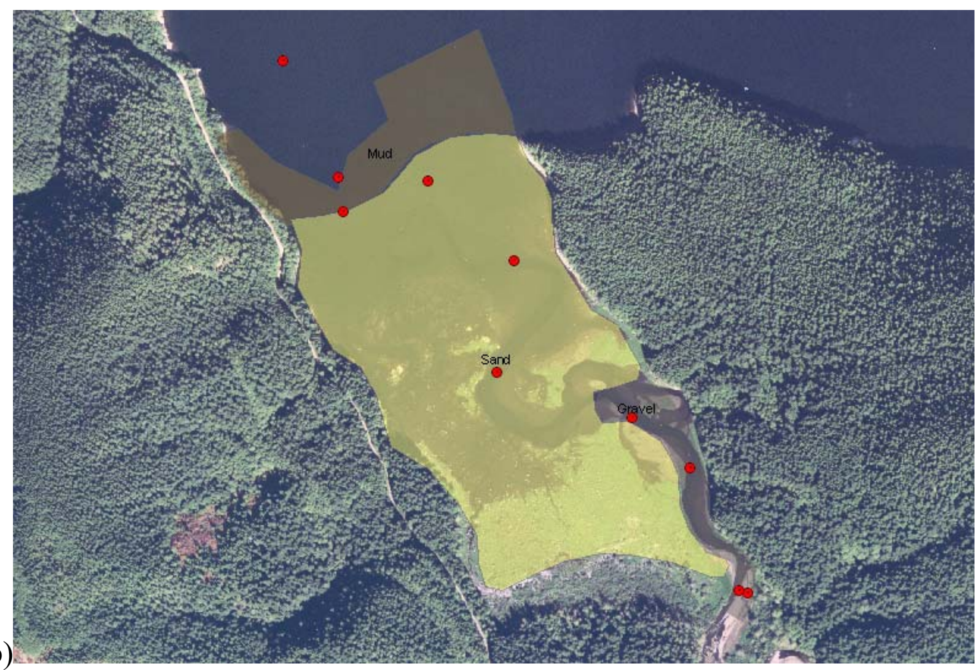
Overall, the apparent slow expansion of the deltas is consistent not only with the idea that the sediment load is low, but also with the age of the lake. As discussed in Section 2.2, Cedar Lake has existed since the last glaciation approximately 12,000 to 14,000 years ago. A previous study concluded that the Cedar and Rex deltas are essentially remnants from the glacial era, during which the deltas formed when the sediment loads were likely much higher (Hong, 1988). In fact, Hong (1988) speculates that the deltas are currently undergoing net degradation and construction of the dams and reservoir has helped to preserve the delta deposits by slowing the degradational process.

4.1.4 Bed Material Sediment Sampling

To approximate the distribution/extent and general characteristics of surficial sediment deposits, samples were collected on both the Rex and Cedar deltas. Access was achieved by boat and samples were collected using a Ponar grab sampler. This type of sampler is a spring loaded bucket that snaps shut when it hits the bottom. Once shut the sampler can be pulled back to the surface and the sediment can be examined. The intention was to sample the main channel; however, its location was increasingly difficult to determine in the downstream direction on the delta as the channel becomes much less defined. Once samples were collected, they were visually classified as mud (silt and clay), sand, or gravel and returned to the reservoir; restrictions on potential impacts to cultural resources limit extensive disturbance of soil/substrate in many areas and do not support removal of sediment from the watershed.



(a)



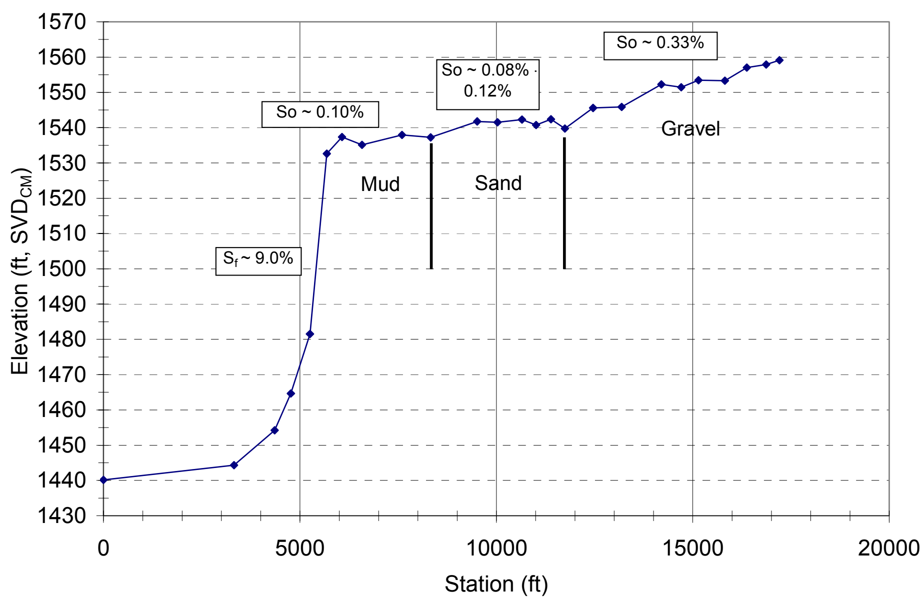
(b)

Figure 4. Estimated surficial sediment deposits and sample locations on the Cedar (a) and Rex (b) deltas.

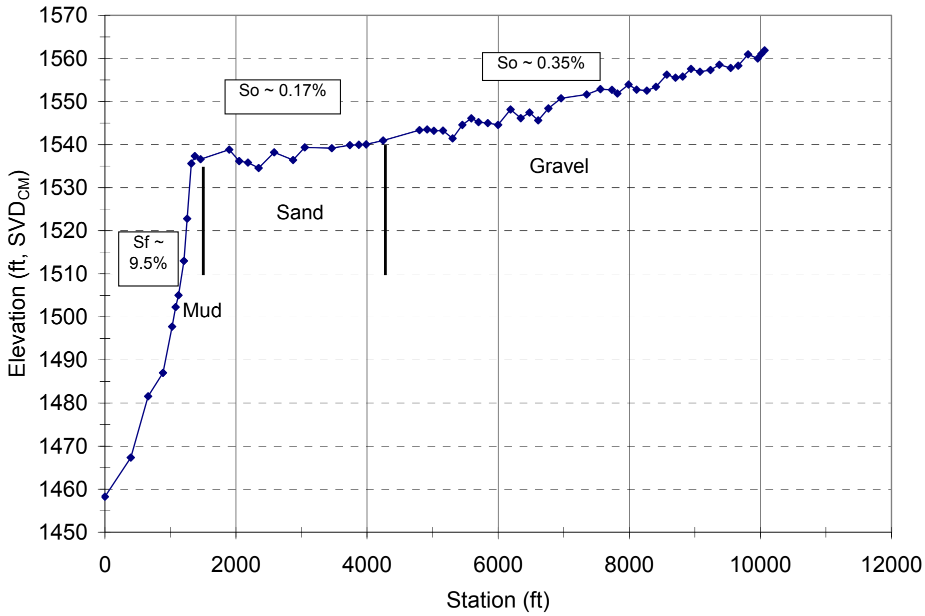
Figure 4a-b shows the locations where samples were taken (red points), as well as the estimated locations of breaks between the channel surface sediment types. On the Cedar, delta samples indicate that extensive mud deposits exist within the channel while on the Rex delta the mud channels are much shorter. The sand and gravel deposits on the two deltas appear to be similar in grain size and extent.

The purpose for taking the samples in the channel is that any potential erosion of the delta topset will likely first proceed through the channel corridor. Undoubtedly, the surficial as well as stratigraphic variations of sediment deposits on each delta are complex. Observed characteristics of the channel surface sediment types are also used in the sediment transport capacity computations, as will be discussed in Section 4.3.3.

Figure 5a-b shows the existing longitudinal profiles of the Cedar and Rex deltas and approximate locations of the breaks between channel surface sediment types. Also included are the measured bed slopes (S_o) for the mud, sand, and gravel reaches, as well as the foreset slope (S_f).



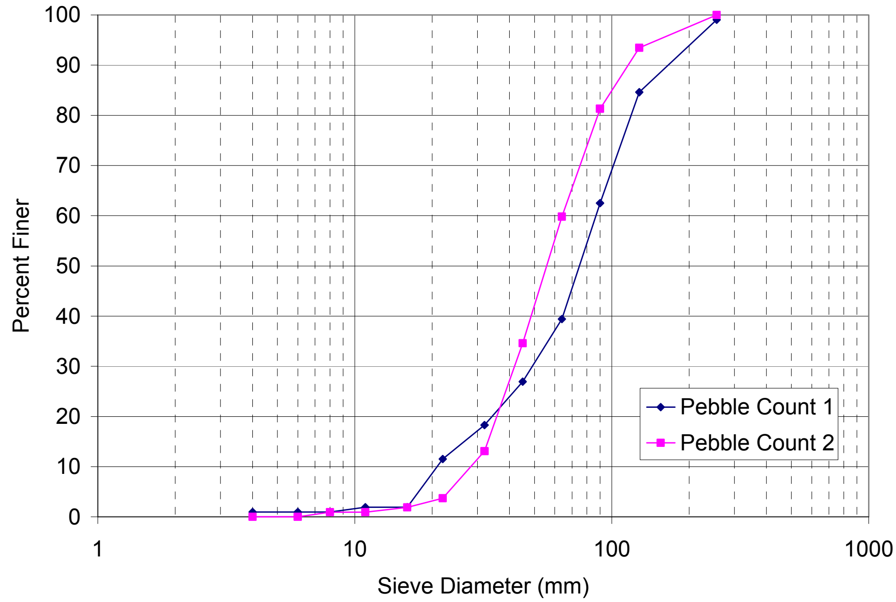
(a)



(b)

Figure 5. Existing longitudinal profile with sediment breaks on the Cedar (a) and Rex (b) deltas.

Wolman pebble counts were also performed on both the Cedar and Rex Rivers to determine the substrate characteristics in the gravel channels upstream of the deltas. The procedure for a Wolman pebble count consists of randomly selecting and measuring the diameter of approximately 100 pieces of substrate material collected by hand from a pre-determined test area on the streambed. Two counts were conducted on both the Cedar and the Rex, with the exact locations of the samples indicated by the two upstream-most points on the respective reach shown in Figure 4a-b. The sample locations on both study reaches lie between the current typical low pool elevation and the high water inundation limit. Similar to the limited sediment samples taken on the delta topset discussed above, the gravel sampling regime was mainly intended to provide median substrate sizes for use in the sediment transport capacity computations. Particle size distributions of these gravel deposits are shown in Figure 6a-b.



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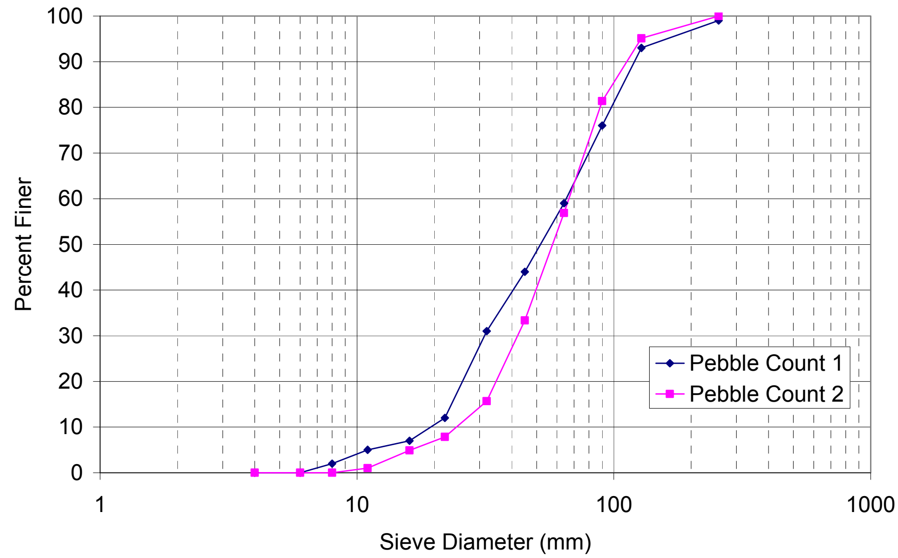


(b)

Figure 6. Particle size distributions from Wolman pebble counts on the Cedar (a) and Rex (b) Rivers.

Based on the Wolman pebble count results, the gravel characteristics are similar for both rivers. The median particle diameter (D_{50}) ranged from 2.2 to 2.9 in (56-75 mm) on the Cedar and 2.1 to 2.3 in (53-58 mm) on the Rex.. However, the significance of these similarities is minimal considering the limited number of samples taken.

4.2 Hydraulic Characteristics of Drawdown and Refill Operations

4.2.1 Hydraulic Model

Hydraulic conditions on the Cedar and Rex Rivers were evaluated using the U.S. Army Corps of Engineers' one-dimensional, steady-state HEC-RAS computer model (USACE, 2005). For this analysis, the hydraulic model was primarily used to provide estimates of sediment transport capacity under different river flow conditions and reservoir levels. Hydraulic conditions such as velocity and flow depth were computed with the model and utilized to assess erosion and sediment transport characteristics, as well as channel hydraulic conditions that typically occur during time periods of bull trout spawning (late Sept. through early Jan.). Results from the HEC-RAS models relevant to the morphologic analysis and sediment transport capacity are discussed below in Section 4.3.3; whereas, the computed velocities and flow depths are presented in Section 4.4.

Separate hydraulic models were built for both the Cedar and Rex study reaches. Both reaches, approximately 3.3 miles in total length on the Cedar and 1.9 miles on the Rex, begin in the reservoir, continue over the delta foreset and topset, and extend upstream into the channel corridor. Input channel geometry for each hydraulic model was based on the TIN constructed by the survey data recently collected by SPU as discussed in Section 2.3.1. The Cedar and Rex models included 25 and 61 cross-sections, respectively. The shorter Rex study reach initially contained a similar number of cross-sections to that of the Cedar, but was later augmented with additional sections to capture more channel and floodplain features. Cross-section locations, as well as the model TIN extents are shown in Figure 7a-b.

(a) 

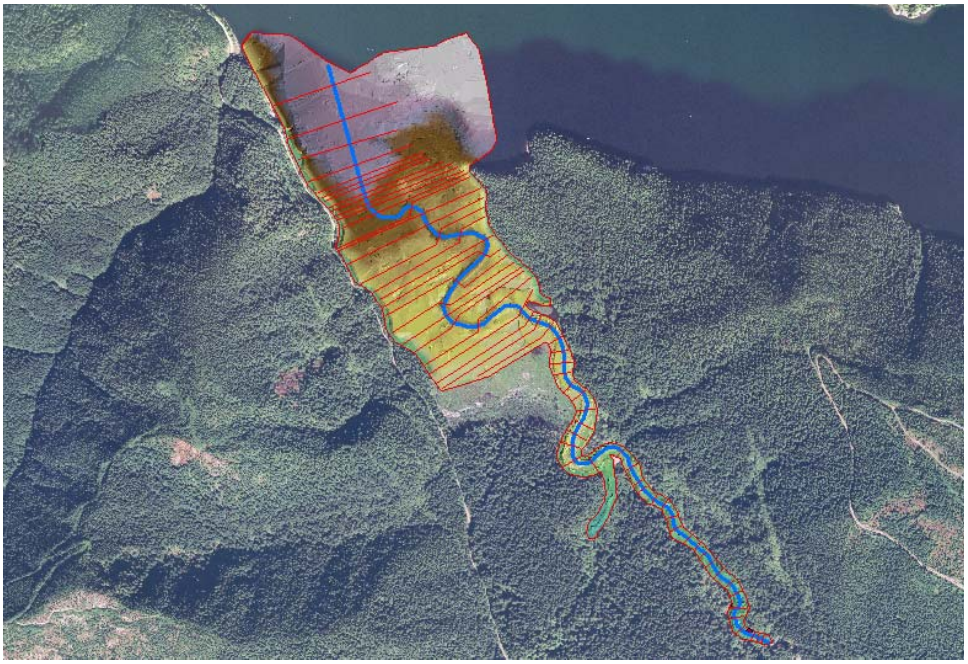
(b) 

Figure 7. HEC-RAS cross-section location on the Cedar (a) and Rex (b) Rivers.

4.2.2 Boundary Conditions

The boundary conditions for the hydraulic model consist of input river flows at the upstream end, and a reservoir water surface elevation at the downstream end. Input river flows were evaluated at discharges ranging from 25 cfs to the 2-year recurrence interval flows of 2,797 and 2,074 cfs for the Cedar and Rex, respectively. It should be noted that the estimated recurrence interval flows for the Rex River where increased by approximately 25% to account for inflow at Boulder Creek.

The downstream boundary conditions for both hydraulic models are effectively controlled by the sharp precipice found at each foreset crest. This occurs because when the reservoir water surface elevation drops below the foreset crest elevation (i.e., 1,538 ft), the computed hydraulic conditions upstream become independent of the reservoir level. *As a result, the selection of a reservoir water surface elevation between 1,538 ft and 1,518 ft becomes arbitrary from a hydraulic standpoint*. For this analysis, the reservoir water surface elevation was set to the minimum estimated drawdown level of 1,518 ft. Assuming the minimum elevation for the proposed reservoir operations provided a limit to the maximum vertical channel adjustment that could be expected.

4.3 Morphologic Modeling

4.3.1 Model Description

A 'conceptual' morphologic model was developed by **nhc** to evaluate the morphologic changes expected to occur as a result of the proposed changes in reservoir operation. This model is not intended to represent the dynamic nature of a fluvial delta, but rather simplifies the system both spatially and temporally. The model presumes a final morphologic condition, then utilizes computed hydraulic quantities to evaluate the rates and durations involved to achieve that final, future condition.

The future conditions of each channel are predicted from empirical relationships that relate flow discharge to channel width and slope, i.e., channel regime relationships. Hydraulic quantities, particularly the sediment transport capacity, are then computed with a steady-state, 1-dimensional, HEC-RAS hydraulic model. The volumes of sediment stored in each delta are then calculated by using results from the regime relationships and the proposed future reservoir operations, i.e., minimum reservoir drawdown elevation. Knowing these sediment volumes and transport capacities, the time required to mobilize and erode the material from the deltas is then computed. The computed durations are then evaluated with respect to the joint probability and durations from the hydrologic analysis discussed in Section 3.6.

4.3.2 Channel Regime Relationships

The U.S. Army Corps of Engineers developed a group of stable channel regime relationships relating bankfull channel dimensions and slopes as a function of the estimated bankfull discharge and surface sediment characteristics (USACE, 1994). Channel dimensions considered include bankfull depth and width, and channel slope. Graphical illustrations of the relationships, from USACE (1994), are included in Appendix D.

Summarized in Table 6 are the values estimated from the regime relationships for the sand/mud and gravel reaches of the Cedar and Rex Rivers. These values were used to estimate channel dimensions, particularly the width, that could be expected to develop within the deltas under the new operations.

Table 6. Bankfull Channel Dimensions and Slopes (USACE, 1994)

		Mud – Sand			**Gravel**		
River	**2-yr Discharge (cfs)**	**Bankfull Width (ft)**	**Bankfull Depth (ft)**	**Slope (ft/ft)**	**Bankfull Width (ft)**	**Bankfull Depth (ft)**	**Slope (ft/ft)**
Cedar	2,800	150	8	0.0004	110	4	0.004
Rex	2,100	125	7	0.0004	65-100	4	0.004-0.005

For this analysis, the 2-year recurrence interval discharge was assumed to represent the bankfull discharge. This assumption seems to be supported by two factors. First the hydraulic models generally predict that flow is contained within the banks up to the 2-yr discharge on both rivers. And second, there is agreement between the Corps' regime relationships and the surveyed channel dimensions in the upper, gravel portions of both the Cedar and Rex Rivers. Here, the average channel gradients for both rivers range from approximately 0.35%-0.38%, and bankfull widths range from 80 to 130 ft on the Cedar, and 55 to 90 ft on the Rex. In the mud/sand reaches of both rivers, the observed channel dimensions appear to deviate from the regime relationships, but this is likely the effect of inundation from high reservoir levels for much of the year, especially during seasons when high flows occur (i.e., late fall to early summer).

4.3.3 Channel Evolution

Evolution of the channel on the Cedar and Rex deltas, as a result of the revised reservoir operations, will undoubtedly be highly dynamic with rapid changes occurring both laterally and vertically. To discretize the morphologic model, divisions were made on each delta at locations where surface sediment characteristics change as shown previously in Figure 5a-b. This discretization effectively creates three uniform volumes of sediment deposits, i.e., mud, sand, and gravel that can be mobilized under competent flows. It was then assumed that the channel would degrade vertically down to an elevation 1 ft below the extreme low water elevation of 1,518 ft. Channel widths were then adjusted using the Corps' regime equations with widths of 150 ft and 125 ft selected for the Cedar and Rex, respectively. Side slopes of the degraded channel were assumed to maintain a 3H:1V ratio. These channel adjustments were then applied to the appropriate cross-sections in the HEC-RAS models. To illustrate, a typical cross-section from the delta region of the Rex hydraulic model (RS 1457) before and after the channel adjustment is shown in Figure 8.

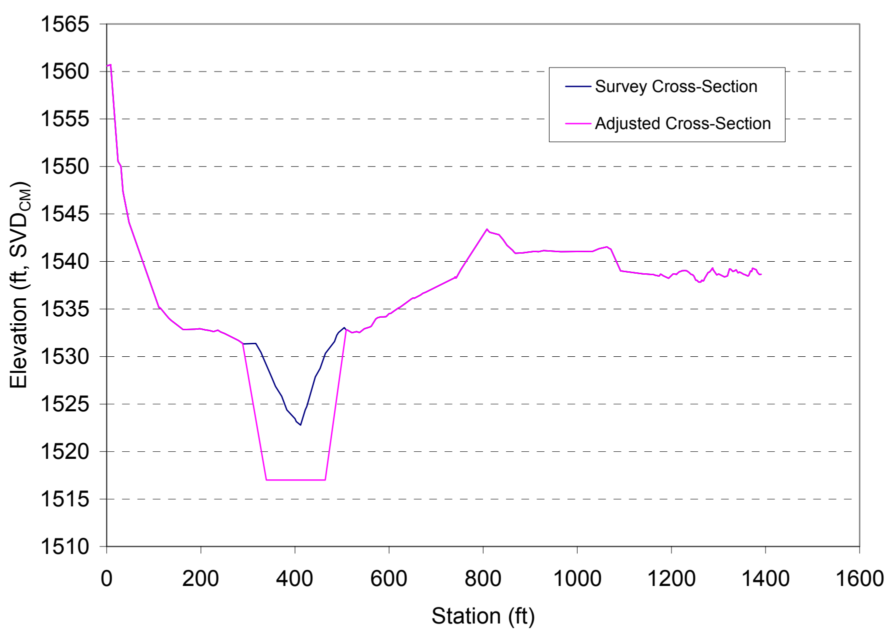
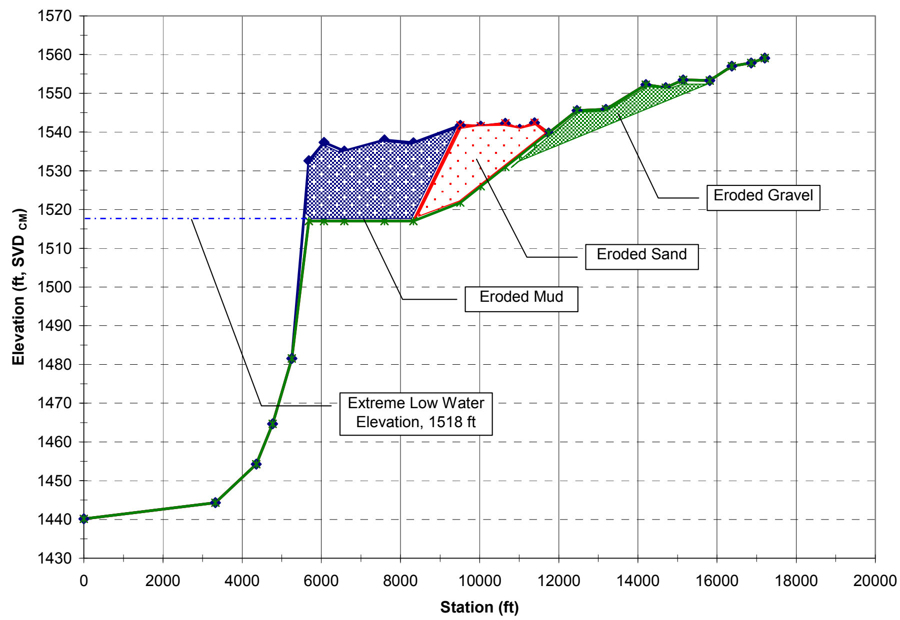


Figure 8. Typical cross-section before and after channel adjustment.

As previously stated, adjustments were made incrementally to the different volumes of the deltas, as defined by observed surface sediment characteristics, i.e., mud, sand, and gravel. Figure 9a-b shows the adjusted long profiles of the Cedar and Rex deltas that include the existing, eroded mud, eroded sand, and eroded gravel profiles. Not shown on these profiles is downstream deposition of eroded material transported from upstream.



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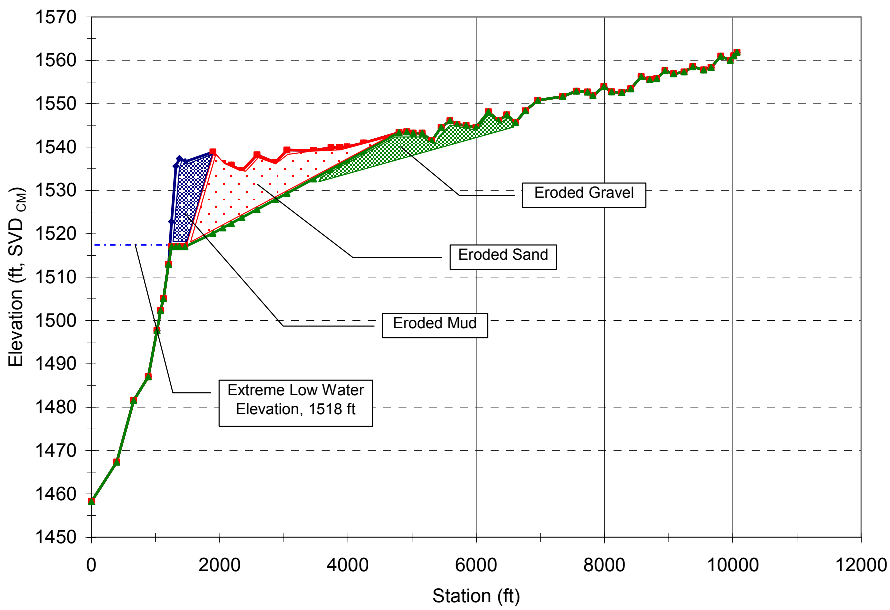


(b)

Figure 9. Long profile evolution of the Cedar (a) and Rex deltas (b).

These profiles *approximate* the longitudinal adjustments that are expected to occur as a result of the revised reservoir operations, but are not intended to be physically realistic. Primarily, the profiles illustrate the maximum volume of each uniform mud, sand, and gravel deposit that could be eroded when the reservoir level reaches the estimated minimum elevation of 1,518 ft. Furthermore, the steep faces, up to 20 ft in height, shown in the existing and eroded mud conditions are not likely to occur. In reality, vertical adjustments followed by downstream deposition will gradually decrease the channel gradient. The rate at which this will occur will likely be on the order of the rate the reservoir is lowered, as observed during the Lake Mills experiment discussed in Section 2.4. Transient morphologic features are also likely to occur on the deltas during drawdown, and are discussed in Section 4.4.

After the sand is eroded it is assumed that the bed will primarily consist of gravel. As illustrated in Figures 9a-b, the profiles for the eroded sand condition include an "over-steepened" bed slope of approximately 0.8%. The Corps' regime relations discussed in Section 4.3.2, predict slopes of 0.4-0.5%, while the existing channel slopes of the gravel reaches upstream, on both the Cedar and Rex, are on the order of 0.35%. The reason the 0.8% slope was used was to allow the predicted profile to remain in the spatial constraints of the existing delta, thus not requiring an extension of the model's spatial domain, i.e. downstream deposition. As a result, the eroded sand condition profiles shown above are expected to degrade further and will likely coincide with the delta extending further into the lake. This extension will include expansion of the gravel reach lakeward and to lower elevations, with the final morphology of the newly eroded gravel reach likely resembling the pool-riffle-glide sequences observed in the current gravel reach.

Sediment volumes illustrated in Figures 9a-b were computed using the estimated cross-sectional adjustments in area and the measured lengths of the reaches. The results indicate that approximately 930,000 and 340,000 cu. yd. of material would be mobilized and removed from the Cedar and Rex deltas, respectively. Additional material will likely be removed from lateral, bank erosion once the channels stabilize vertically.

Hydraulic conditions, as computed in the HEC-RAS hydraulic model, were evaluated at each stage of the delta evolution. Sediment transport functions included with HEC-RAS were used to compute average transport capacities between cross-sections. These functions tend to lend themselves better to certain sediment conditions, thus specific functions were selected for the mud/sand reaches and the gravel reaches. For the mud and sand reaches, the Engelund-Hansen and Ackers-White total load transport functions were selected. Both of these functions estimate the bed and suspended load, i.e., total load. In the gravel reaches, the Meyer-Peter Muller and Yang bedload relations were applied. Multiple relations were used because transport functions can yield results that are often different by an order-of-magnitude. To account for this, the results from the relationships were averaged. The averaged sediment (mud/sand and gravel material) rating curves for both the Cedar and Rex Rivers are presented in Figure 10.

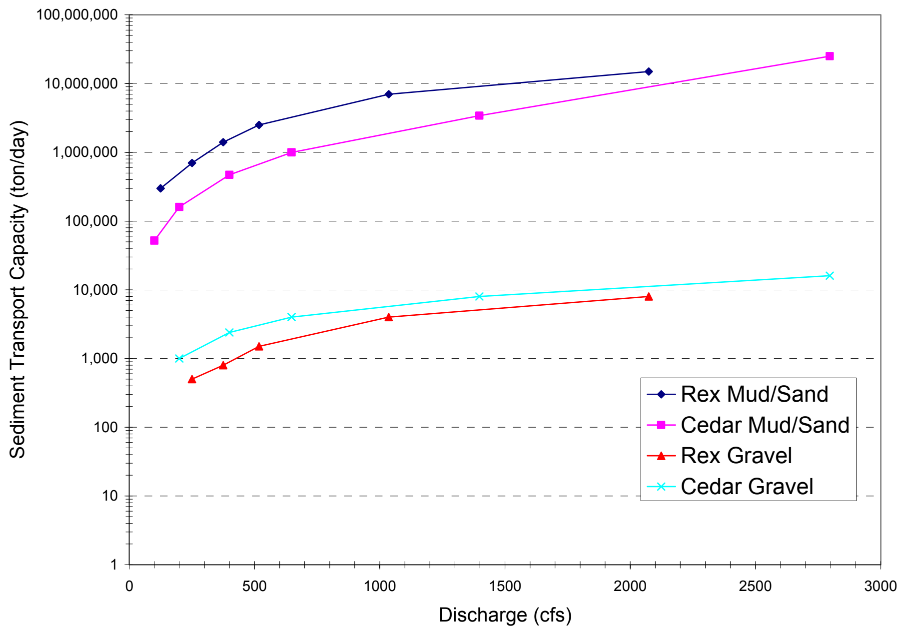


Figure 10. Sediment transport rating curves for mud/sand and gravel material.

The upper set of curves shows the variation in transport capacity for finer, mud/sand material (ton/day) as a function of water discharge (cfs). Similarly, the lower curves give the estimated transport capacity for gravel material. Both sets of curves illustrate the exponential increase in transport capacity as a function of discharge. Rates of transport are seen to vary from 10,000 to over 20,000,000 ton/day for finer material, and 500 to almost 20,000 ton/day for coarser material. Without the aid of calibration, however, data to verify the accuracy of these curves should be interpreted as order-of-magnitude estimates of sediment transport capacity.

Knowing approximate volumes of sediment available in the deltas and the rates at which they could be transported allows for the estimation of time required to erode the material. Figure 11 shows duration curves that indicate the time required for the specified deposits to erode as a function of discharge. Of particular interest are the curves for mud/sand. These curves indicate that at lower (and more frequent) discharges, i.e., less than 100 cfs, mud and sand deposits could be expected to erode on the order of days to weeks. These variations in time are due not only to the different estimated transport rates, but also the different volumes of material contained in each delta. At higher discharges the deposits are predicted to erode at exceptionally rapid rates requiring less than a day; although, at these rates the absolute accuracy of the duration becomes questionable. Regardless, the overall process is that of liquidation of the fine mud and sand materials and rapid channel degradation that occurs over a very short period.

For gravel materials, the duration curves reflect the lower transported rates expected. At the lowest flows evaluated, the durations extend into years; however, the competency of flows on the order of 25 cfs to even mobilize gravel is questionable. As such, the estimated gravel transport and durations *at low flows* should probably not be relied upon. More important, are the higher, more competent flows. In this range the duration for channel degradation is predicted to be on the order of weeks to months.

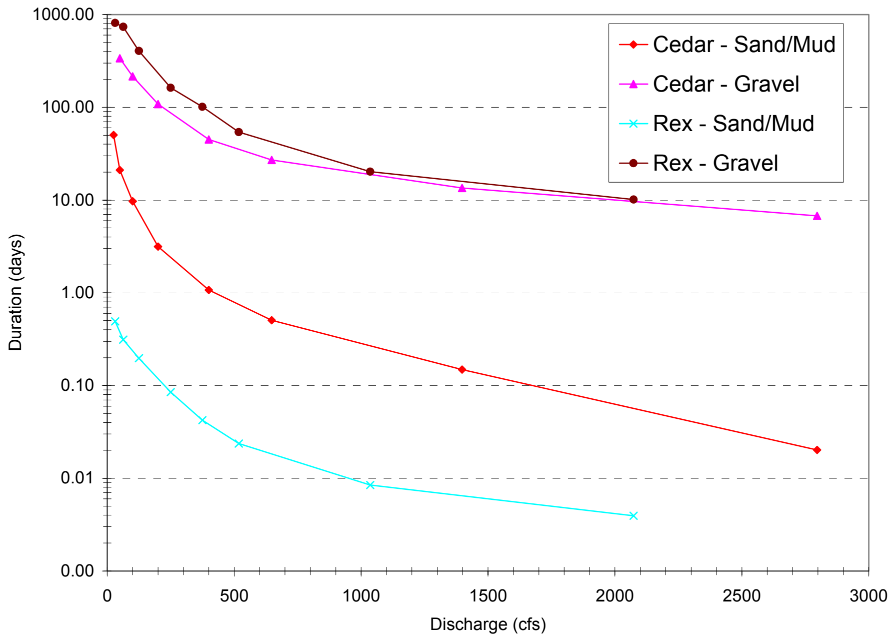


Figure 11. Time required for the specified deposits to erode as a function of discharge on the Cedar and Rex deltas.

As previously summarized in Section 3.6, the joint occurrence of low reservoir levels with upstream discharge (statistically similar on both the Cedar and Rex Rivers) indicate that flows competent to move substantial material (100 to 200 cfs) occur in approximately 30% of the years with reservoir elevations below 1,532 ft, and 20% of the years below 1,525 ft. In other words, the upper 6 to 8 ft of the deltas would be exposed to flows competent to erode substantial material 1 in 3 years, while the upper 18 to 20 ft will be exposed 1 in 5 years. The average duration of these events are estimated to last approximately 20 to 25 days, and 9 to 17 days, respectively. Based on the estimated times required to transport material these average durations will provide ample time to transport much of the finer mud and sand material from each delta during a given year.

Over the 70 years of simulated "with project" reservoir operations, there were 24 dry years in which pumping was projected to cause reservoir drawdowns below the topsets of the existing Morse Lake deltas in the late summer and fall. During 2 of these 24 years (1953 and 1988), freshets exceeding 100 cfs of mean daily flow do not occur until December. Thus, under the assumed project scenario, there is annually about a 3% chance that during the fall spawning period (September-November) the existing delta topsets would be exposed and no freshets would occur that could transport gravel. This analysis indicates that there is a non-zero probability of static gravel during the preferred spawning period and a potential migration barrier might result from this.

Based on the statistical analysis, the deltas on the Cedar and Rex can be expected to degrade, to a final low reservoir level sometime in the first 5 years after reservoir operations are changed, with significant erosion of the deltas likely to occur in the first 3 years. Furthermore, the average duration of transport events are sufficient to allow full vertical adjustment of the deltaic channels within a single year or season. The implications of these findings are that it will likely take 3 to 5 years for a full channel adjustment to occur, but it is also entirely possible for it to occur in a single season.

4.4 Hydraulic Characteristics of Cedar and Rex River Delta Channels During Channel Adjustment

In addition to sediment transport estimates, the HEC-RAS hydraulic models yield estimates of the basic hydraulic conditions such as channel velocity and flow depths along the Cedar and Rex study reaches for both existing reservoir operation and proposed drawdown operation conditions. Discharges evaluated range from 25 cfs to the 2-year recurrence interval flow. These flows are representative of flow conditions that occur during bull trout spawning activity in these rivers. As discussed in Section 4.2.2, the hydraulic conditions on the delta are independent of reservoir level due to critical flow at the delta topset-foreset interface, thus, the reservoir surface elevation was set to 1,518 ft for both conditions.

Tables 7 and 8 report reach-averaged and peak velocities for conditions over the existing delta channels and those after the mud and sand have been eroded on the Cedar and Rex Rivers, respectively. Here, the eroded mud/sand condition essentially represents the most extreme anticipated condition where the bed consists of a steep gravel reach (see Figures 9a-b). A subsequent reworking of the gravel bed and reduction in channel gradient, however, is likely to occur over durations lasting one to several years, as discussed in Section 4.3.3. As a result, the gradients for the extreme condition may over predict velocity slightly as the bed profile is steepened over the regime gravel channel slope.

Table 7. Reach-Averaged and Peak Velocities on the Cedar River Delta

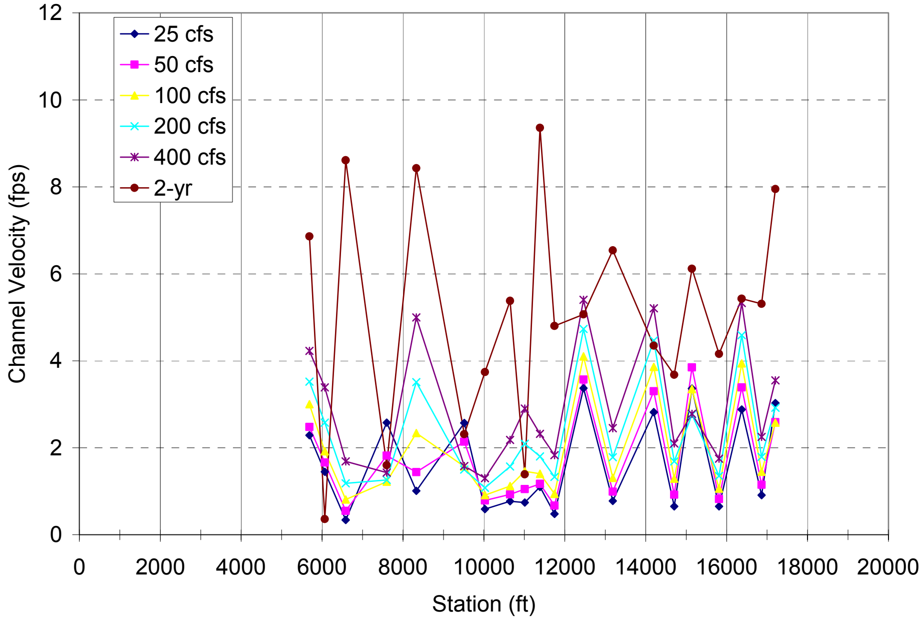
	Mud Reach		Sand Reach		Gravel Reach	
Delta Condition	Reach Avg Vel (fps)	Peak Vel (fps)	Reach Avg Vel (fps)	Peak Vel (fps)	Reach Avg Vel (fps)	Peak Vel (fps)
Initial	2-4	9	2-4	9	2-4	8
Eroded Sand/Mud	1-3	8	2-6	11	2-4	8

Table 8. Reach-Averaged and Peak Velocities on the Rex River Delta

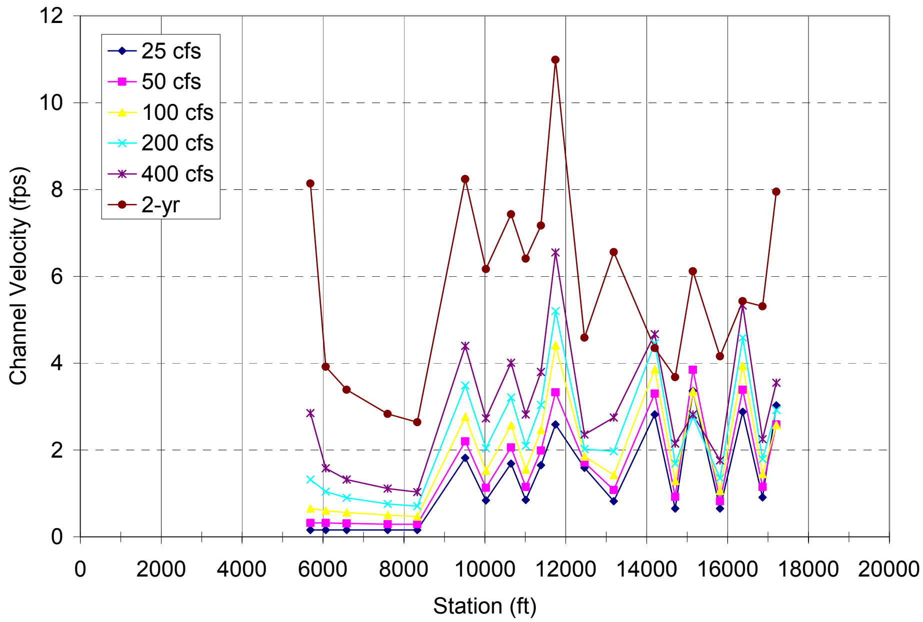
	Mud Reach		Sand Reach		Gravel Reach	
Delta Condition	Reach Avg Vel (fps)	Peak Vel (fps)	Reach Avg Vel (fps)	Peak Vel (fps)	Reach Avg Vel (fps)	Peak Vel (fps)
Initial	1-2	10	2-3	6	2-4	8
Eroded Sand/Mud	2-4	9	3-4	7	2-4	8

The results given in Tables 7 and 8 show that both reach-averaged and peak velocities are not expected to change substantially as a result of the proposed reservoir drawdown. For initial conditions, the reach-averaged velocities for all reaches do not exceed 4 fps, while localized peak velocities range from 8 to 10 fps. It should be noted here that the highest peak velocities were computed for 2-year recurrence interval flows. Peak velocities were less than 6 fps for flows less than 400 and 300 cfs on the Cedar and Rex river channels, respectively. For the eroded mud/sand conditions, the computed changes are generally minor, reach-averaged velocities in both the mud and gravel, with 1 to 2 fps increases observed in the central sand reach.

Figures 12a-b and 13a-b show the computed variations of channel velocities along the study reaches of the Cedar and the Rex Rivers, respectively. The first figures (a) of each set show velocities of initial conditions, and the second figures (b) are the velocities computed for the eroded mud/sand condition. Velocities associated with flows between 25 and 400 cfs, as well as the 2-year discharge, are shown. It should be noted that each point of a curve is the velocity computed within the channel at a cross-section in the hydraulic model.

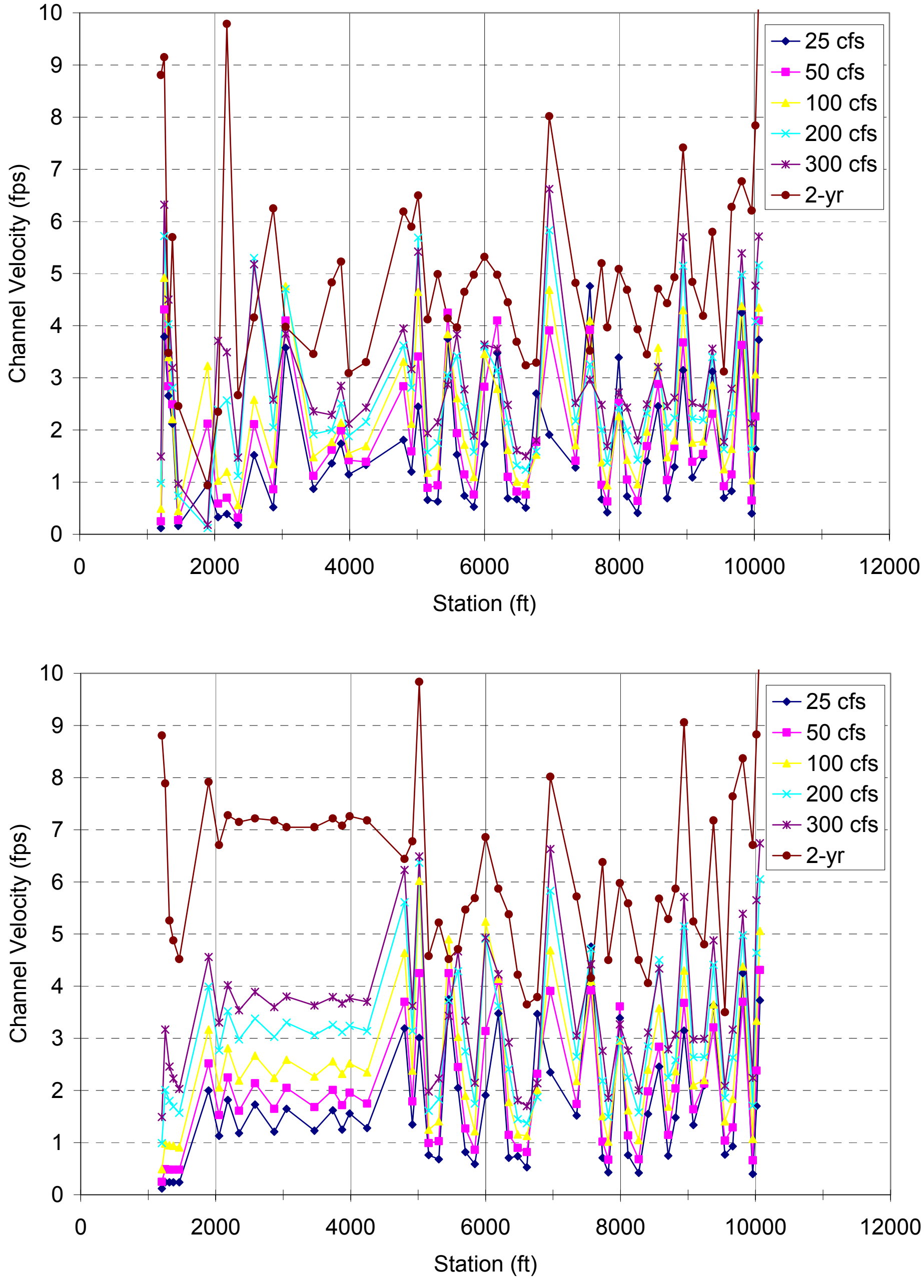


(a)



(b)

Figure 12. Computed channel velocities on the Cedar River prior to delta erosion (a) and after (b).



(a)

(b)

Figure 13. Computed channel velocities on the Rex River prior to delta erosion (a) and after (b).

Tables 9 and 10 report reach-averaged and peak hydraulic depth (H_d) for initial and the eroded mud/sand conditions on the Cedar and Rex Rivers, respectively. Channel hydraulic depth, defined as the channel flow area divided by channel width, was selected as a key variable as it provides an average flow depth across the channel portion of the cross-section.

Table 9. Reach-Averaged and Peak Hydraulic Depth on the Cedar River Delta

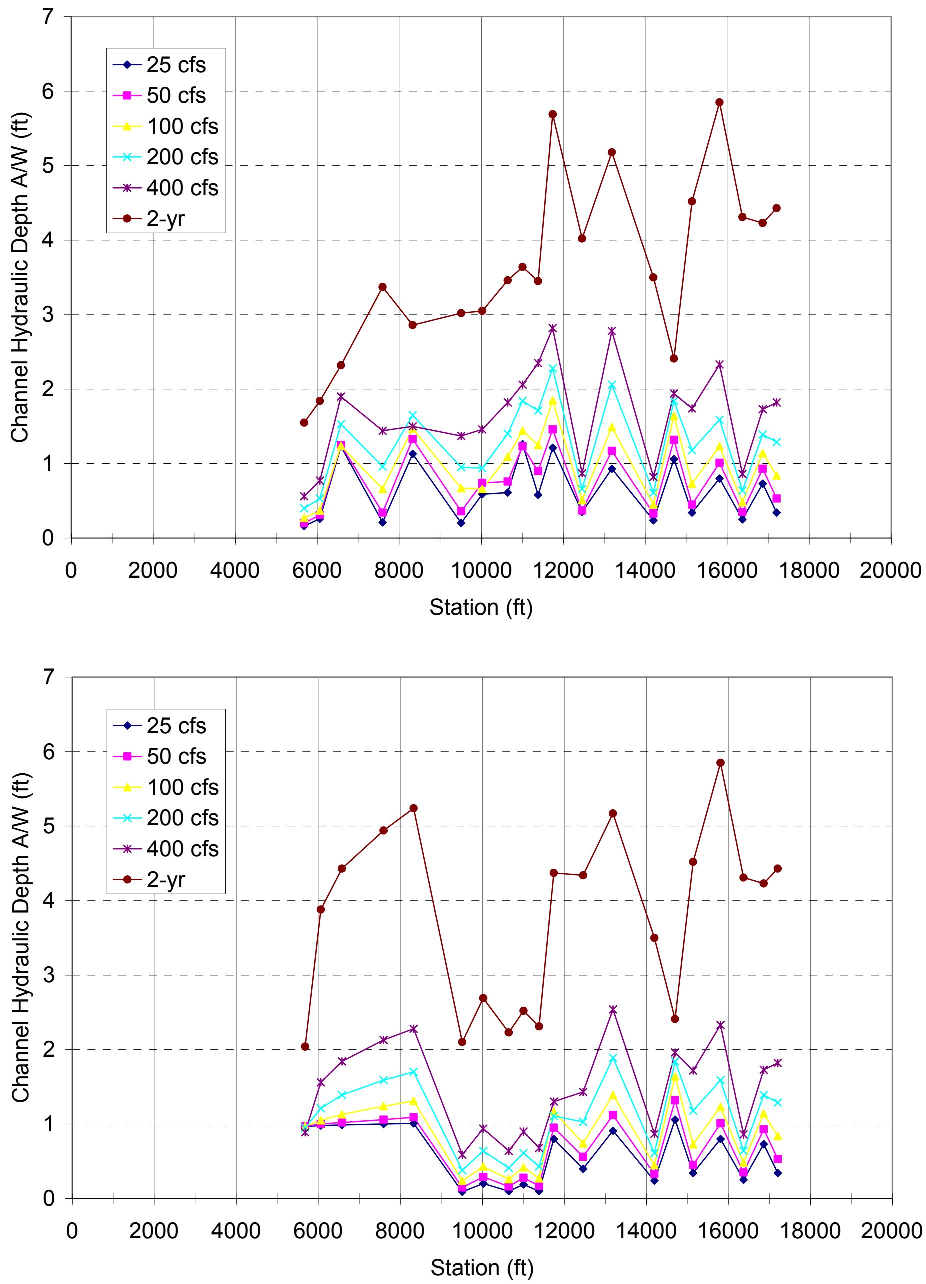
Delta Condition	Mud Reach		Sand Reach		Gravel Reach	
	Reach Avg H_d (ft)	Peak H_d (ft)	Reach Avg H_d (ft)	Peak H_d (ft)	Reach Avg H_d (ft)	Peak H_d (ft)
Initial	0.5 - 1	3.5	0.75–1.5	5.5	0.75–1.5	6
Eroded Mud/Sand	1.0-2.0	5	0.25-0.75	2.5	0.75–1.5	6

Table 10. Reach-Averaged and Peak Hydraulic Depth on the Rex River Delta

Delta Condition	Mud Reach		Sand Reach		Gravel Reach	
	Reach Avg H_d (ft)	Peak H_d (ft)	Reach Avg H_d (ft)	Peak H_d (ft)	Reach Avg H_d (ft)	Peak H_d (ft)
Initial	0.5-1.5	3.0	1.0-2.0	5.5	0.5-1.5	5.0
Eroded Mud/Sand	0.25-1.0	3.0	0.25-0.75	5.5	0.5-1.5	5.0

For initial conditions, the reach-averaged hydraulic depths for all reaches range from 0.5 to 2 ft. Computed peak hydraulic depths increase significantly and range from 3.5 to 6 ft. Similar to computed peak velocities, the peak values of hydraulic depth are associated with the 2-year recurrence interval discharge. For the eroded mud/sand conditions, the computed changes show a decrease in hydraulic depth mostly in the central sand reaches of the Cedar and Rex deltas with reach-averaged values that range from 0.25 to 0.75 ft.

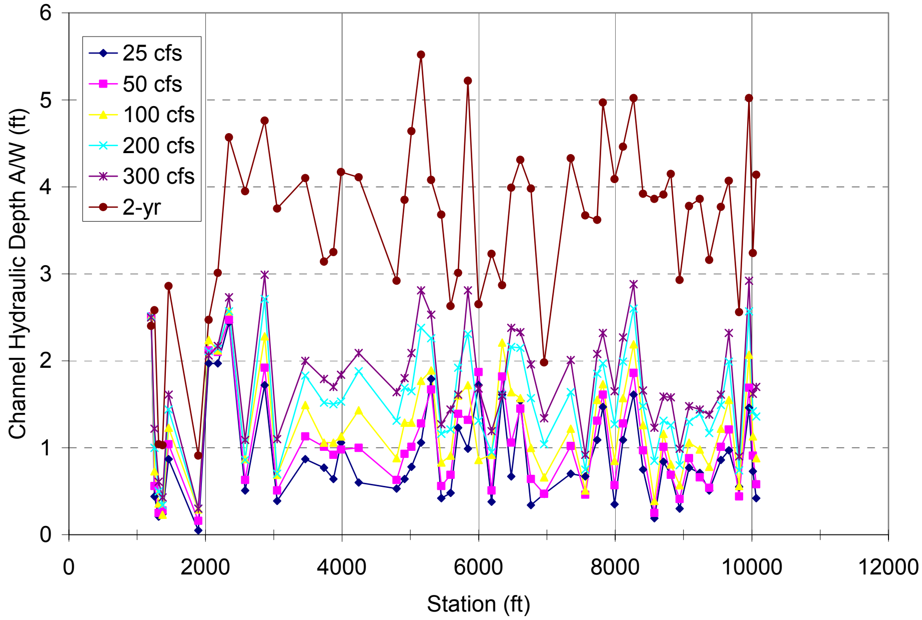
Figures 14a-b and 15a-b show the computed variations in channel hydraulic depth along the study reaches of the Cedar and the Rex Rivers, respectively. Again, the first figures of each set shows hydraulic depth for initial conditions, and the second are computed with the sand and mud portions eroded.



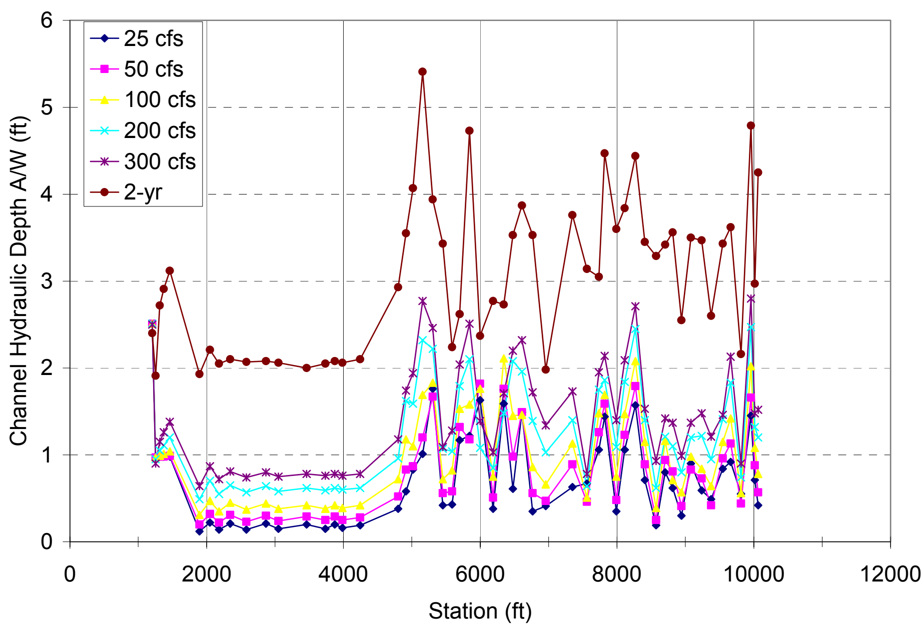
(a)

(b)

Figure 14. Computed channel hydraulic depth on the Cedar River prior to delta erosion (a) and after (b).



(a)



(b)

Figure 15. Computed channel hydraulic depth on the Rex River prior to delta erosion (a) and after (b).

4.5 Transient Morphologies

4.5.1 Knickpoints

The morphologic model and channel evolution estimates discussed above do not consider transient, morphologic features that will occur between the onset of delta degradation and the final, dynamic equilibrium of the channel. One feature expected to occur, and the one that potentially represents the greatest physical barrier to fish passage, is the knickpoint. These features occur in many forms and under different conditions, but generally consist of an abrupt drop in bed elevation within the channel.

There are several potential origins under which knickpoints can form and persist. Two common origins include base-level lowering which occurs when a reservoir is lowered and exposes a delta front, while another origin consists of spatial changes in the erodibility of substrate. In addition, a potential third origin may be attributed to instabilities of high velocity flow over erodible beds.

The geometry of knickpoints is also varied, but they are primarily a function of bed material composition. In strongly cohesive material, knickpoints can have nearly vertical faces and maintain their form. As material becomes less cohesive, such as the transition from mud and silt to sand and gravel, the form of knickpoints becomes more gradual as it rotates in profile. Whether the knickpoint maintains a vertical face or it rotates, both are commonly observed to migrate upstream as localized erosion occurs both upstream and downstream of the feature.

At Chester Morse Lake reservoir, a drawdown of water levels below the foreset crest elevation (~1,538 ft) will likely induce the formation of a single knickpoint. As drawdown continues and more of the foreset becomes exposed resulting in high velocity flow over a steep, erodible bed, the possibility of multiple knickpoints forming becomes greater.

Although it is likely that knickpoints will form on the degrading deltas, two factors potentially reduce their adverse impact on fish passage. First, knickpoints are transient features. Under the highly erodible conditions such as those found on the Cedar and Rex deltas this would be especially so. With delta deposits consisting of materials ranging from mud to gravels, relatively rapid knickpoint migration would be expected to occur over days to weeks. Second, since it is not likely that the exposed surficial delta deposits are strongly cohesive, the geometry of the knickpoints are likely to rotate, or flatten out, as they migrate upstream, thus reducing their ability to act as a barrier. However, since some of the deposits expected to be exposed by deltaic erosion may be on the order of 14,000 years old, i.e., deposited during the last glaciation, thus some degree of consolidation and particle cohesion has likely occurred. How this affects knickpoint geometry will depend largely on the degree of cohesion.

The expectation that knickpoints will be transient features and fail to maintain form, and hence not present a persistent barrier to fish passage, is supported by observations made during the Lake Mills Drawdown Experiment, as discussed in Section 2.4. There, knickpoints, as well as standing waves (anti-dunes), were observed to form, migrate upstream, but not persist as they encountered coarser material (USGS, 2000).

4.6 Downstream Deposition and Turbidity

Material eroded from the deltas during drawdown will either be deposited immediately downstream of the existing delta foresets (i.e., sand and gravel) or remain suspended for some period of time (i.e., silt and mud). During the drawdown experiment at Lake Mills on the Elwha River, discussed in Section 2.4, a post-drawdown delta was observed to extend 300 ft beyond the previous foreset face. It was estimated that approximately 300,000 cu yd. of material were transported from the Elwha delta. The total volume of material that could be removed from the Cedar and Rex deltas as a result of reservoir drawdown is estimated at approximately 950,000 cu. yd. and 350,000 cu. yd., respectively. Based on the observations made during the sediment survey discussed in Section 4.1.4, it is estimated that mud and silt compose 50% of the total Cedar delta, but only 16% of the Rex, thus it is expected that the Cedar delta would contribute significantly more suspended sediment to the reservoir than the Rex delta.

Given the amount of fine material that has been mapped in the Cedar delta and to a lesser extent in the Rex delta, it is expected that a significant amount of reservoir turbidity will occur soon after any substantial drawdown. Turbidity events are likely to continue through the period of channel adjustment within the portions of the deltas containing significant amounts of silt or mud. The resultant suspended sediment concentrations and durations of individual turbidity events as well as the period over which events will continue to occur are highly variable and depend on the pattern of flows that occur and management of the reservoir level. Evaluation of the probability distributions of these turbidity impacts require dynamic sediment and geomorphic modeling coupled with Monte Carlos simulations – techniques that go well beyond the scope of the current study.

4.7 Reservoir Refill Conditions

The channels that will evolve as a result of the proposed future reservoir operations will undoubtedly be subject to inundation for a substantial portion of the year. During this time the integrity of the eroded channels could potentially be compromised by two factors: aggradation within the eroded channel from upstream sediment inflow, and structural undermining as a result of submergence (e.g., sloughing, landsliding, and wind/wave induced erosion).

Based on the conclusion that current sediment loads in both the Cedar and Rex Rivers are relatively low, as discussed in Sections 4.1.2, aggradation within the newly eroded channel is not expected to be significant and the eroded channel morphology will persist during reservoir refill conditions. As discussed in Section 4.3.3, this morphology will resemble the pool-riffle-glide sequences and extend further lakeward at lower elevations. Although this morphology will eventually resemble that observed upstream in the existing gravel reaches, the seasonal hydraulic characteristics will be different, i.e. the duration of reservoir inundation of the lower gravel reaches will invariably be greater.

As for structural undermining during inundation, some reworking and sediment movement of channel features may occur, but it is unlikely that it will result in significant aggradation within the channel. The preservation of channel structures as indicated in historical aerials from the 1930's, and discussed in Section 4.1.3, supports this conclusion.

5.0 SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDY

This study presented the results of hydrologic, hydraulic, geomorphologic, and sediment transport analyses of the Cedar and Rex River delta systems with assumed potential changes in the operation of the Chester Morse Lake reservoir to tap current dead storage for normal municipal water supply and instream flow management requirements. The analyses support the conclusion that the reservoir drawdown will lead to erosion of the existing delta deposits and also lead to a steepening of the river channels entering the reservoir during periods of drawdown following the initial reservoir drawdown. The erosion process is expected to be very dynamic, with relatively rapid adjustment of the channel, first through the mobilization of sand and mud deposits, followed by a more gradual adjustment of the channel through movement of the gravel deposits via knickpoint erosion. These erosional processes are a function of both the reservoir stage and inflowing river discharge. Higher river discharges that typically begin with freshets in the fall and extend through the spring will lead to more rapid incision and establishment of a new regime channel through the delta deposits. Channel hydraulic conditions for both existing and eroded channel conditions indicate velocities of approximately 4 to 8 fps and depths of 0.5 to 2 ft for flows typical of the fall flows occurring during time periods of bull trout spawning.

Several measures or studies should be considered to minimize or mitigate for any potential adverse impacts to bull trout spawning due to the proposed drawdown scenario. These recommendations are given below for SPU's consideration.

1. A numerical sediment transport model could be developed to more accurately simulate the interactions between reservoir stage, bed material characteristics, channel hydraulics, and sediment transport. This model would be a relatively straightforward extension of the HEC-RAS model developed for this study, would provide a tool to more accurately quantify the characteristics of the incision process, and be useful to evaluate the effectiveness of operational scenarios and mitigation measures to ameliorate any adverse impacts to spawning passage. We recommend that a 1-dimensional sediment transport model (i.e., HEC-6 or the similar, newly released, mobile bed HEC-RAS) be considered.

2. With this sediment transport modeling tool (see #1 above), the effects of a range of reservoir drawdown scenarios could be directly computed with the objective of minimizing bull trout or pygmy whitefish spawning impedance. These scenarios could include limiting the initial reservoir drawdown to something less than the proposed maximum drawdown to reduce the vertical extent of the knickpoint incision and reduce the time period required to establish a new regime channel though the delta deposits. Subsequent drawdown events in following years could proceed to lower elevations, thus minimizing the amount of erosion required to establish the new regime channel in any given season.

3. The stratigraphy of the delta deposits has been inferred from limited surface sampling and inference based on classical delta sedimentation processes. Of primary concern to the assessment of the channel erosion is the extent of the gravel deposits, as the time required to establish a new regime channel through the gravel materials is on the order of several weeks

for flows typical of the fall drawdown time period. Non-intrusive, subsurface geophysical surveys may provide a more accurate representation of the delta stratigraphy and more accurately simulate the potential response of the delta channels to the proposed drawdown. Outside of detailed subsurface geophysical surveys, the numerical sediment transport model could be readily used to evaluate the sensitivity of the channel response to the assumed extent and characteristics of the subsurface gravel deposits.

4. Managed reservoir drawdown to promote channel degradation during the winter or spring snowmelt runoff season may provide a means to establish the regime incised channel geometry outside of the time period of bull trout spawning. Although reservoir drawdown during the spring reservoir fill operation may adversely affect water supply reliability (e.g., increased turbidity), planning for the operation during a spring season with an appreciably high snowpack may minimize any adverse affect to the water supply capability of the reservoir.

5. A limited test drawdown, outside of the time period for bull trout and pygmy whitefish spawning (late September through early January), should be considered. This test would be similar in character and duration to the Lake Mills drawdown completed on the Elwha River. This test would provide the opportunity to more accurately measure the present delta morphology and topography, and also observe the response of the system to the proposed drawdown. Observations of reservoir turbidity during the drawdown could also be obtained. This limited drawdown would provide a database for sediment transport model calibration for subsequent modeling of more significant drawdown conditions.

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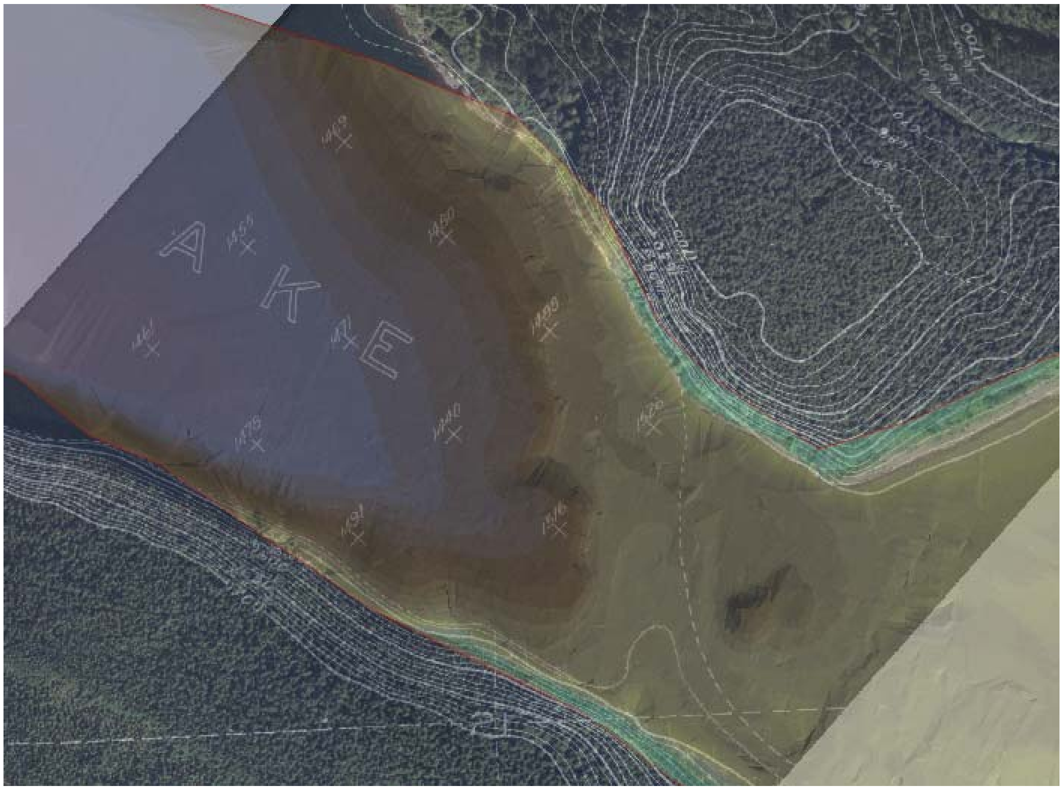
APPENDIX A

Historic Topographic and Bathymetric Maps and Aerial Photos



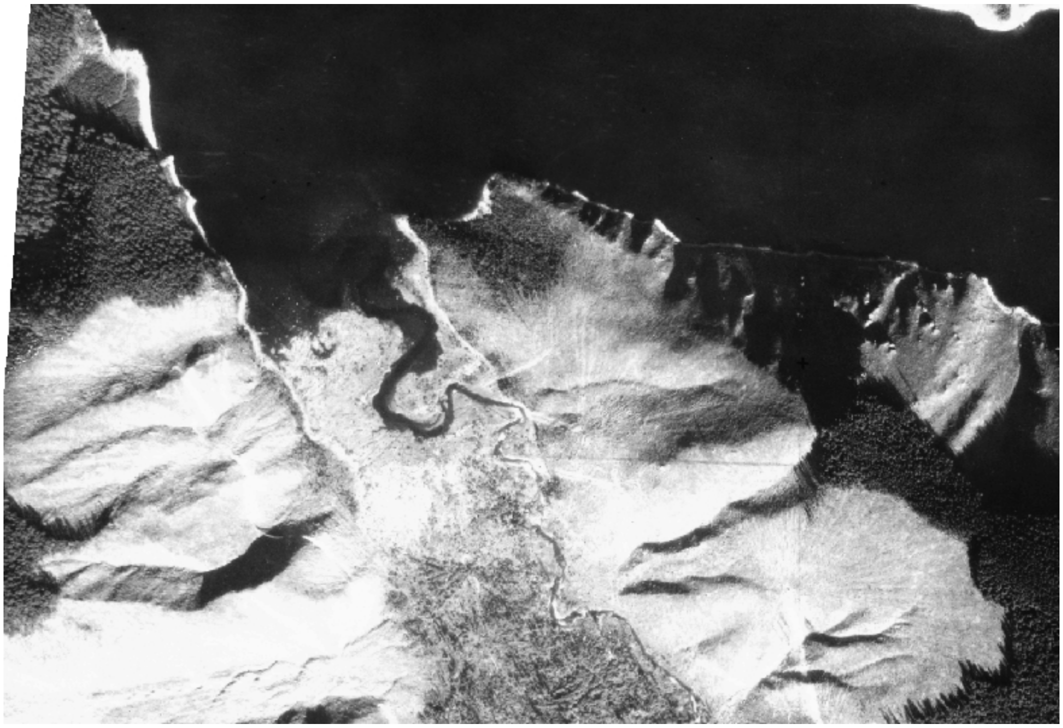
(a)

(b)

Historic topography and bathymetry (c. 1915), overlaying recently surveyed TIN surface on Cedar (a) and Rex (b) deltas.


Cedar River Delta, c. 1930


Cedar River Delta, 2002



Rex River Delta, c.1930

Rex River Delta, 2002

APPENDIX B

Vertical Datum

Vertical Datum

The terrain data elevations received from SPU were originally reported in the North American Vertical Datum of 1988 (NAVD 88); however, because reservoir elevations, also obtained from SPU, were reported in the City of Seattle Vertical Datum (SVD) a conversion was necessary. For this project the SVD was established as the primary vertical datum. As reported on the terrain survey drawings received from SPU, to convert to SVD elevations, 11.17 ft was subtracted from the NAVD88 elevation. Furthermore, the conversion between NAVD88 and the National Geodetic Vertical Datum of 1929 (NGVD29) was found to be +3.75 ft using the Army Corps of Engineers' Corpscon 6.0.1 software.

During the course of this study, however, the accuracy of the conversion between SVD and NAVD88 became questionable. The primary reason for suspicion was that the accepted conversion in the lower Puget Sound basin is approximately 9.7 ft (KCSWDM, 1996). The SPU survey department was alerted to the difference and they proceeded to look into the issue. Their findings indicate that a discrepancy may arise from a 1.33 ft difference between two level loops between Cedar Falls and a benchmark on Masonry Dam performed in 1959 and 1964 (M. Lynch, email). Essentially, SPU established a convention since the 1964 level loop to accept the benchmark elevation set in 1959, which was 1.33 ft lower than surveyed in 1964.

Similarly, the potential discrepancy may carry over to the conversion between NGVD29 and SVD. For example, in the USGS's annual *Water Resource Data* document for Washington, it states that at the Chester Morse Lake gage (12115900), "the datum of the [SPU] gage is 7.39 ft above NGVD29 (levels by City of Seattle)". The value of 7.39 ft is reasonably close to 7.42 ft (i.e. 11.17 ft – 3.75 ft), but it is still inconsistent with the common conversion value of 6.05 ft in the Puget Sound basin (KCSWDM, 1996).

Considering the findings discussed above, it appears the City of Seattle has developed a local "City" datum at Chester Morse Reservoir. In fact, a figure of a topographic map from a consultant's report refers to the vertical datum as the "Seattle Water Department" datum rather than the City of Seattle datum (Hong, 1986). To distinguish between the City datum at the reservoir and the datum within the City limits, the former is referred to as SVD_{CM}.

For this study all elevation data received not in a "City" datum (e.g. terrain data) were converted by **nhc** to the SVD_{CM}, and data received already in a SVD (e.g. reservoir water surface elevations) were assumed to be SVD_{CM}, as per the City's reporting convention.

The conversion equations between the three datums at Chester Morse Reservoir are summarized below.

$$SVD_{CM} = NAVD88 - 11.17 \text{ ft}$$

$$NGVD29 = NAVD88 - 3.75 \text{ ft}$$

$$SVD_{CM} = NGVD29 - 7.42 \text{ ft}$$

APPENDIX C

Hydrology

Hydrology

Upper Cedar and Rex River Basins

The Cedar and Rex rivers are the primary inflow streams to Morse Lake. They drain adjacent forested basins southeast and south-southeast of the reservoir. Drainage areas of the basins are approximately 41 and 22 square miles respectively. Although both basin stream networks terminate in low gradient channels that traverse their respective deltas at Morse Lake, the stream networks as a whole are dominated by steep gradients, with step-pool structure characteristic of Cascade mountain forest streams. The upper Cedar river rises from Morse Lake at an approximate elevation of 1,550 to the Cascade crest at the tops of several peaks including Mount Baldy (el 5,200 ft), Abiel Peak (el 5,365 ft), Tinkham Peak (el 5,395 ft), and Goat Mountain (el 4,773 ft). While the high points of the Rex River basin are generally 1,000 ft lower than the Cedar, the Rex basin's relief ration is approximately 6% compared to approximately 3% for the Cedar because of a much shorter distance from the mouth of the Rex to its basin crest. Median forest stand age is in excess of 65 years in both basins and each is dominated by closed forest canopies including mid-seral (age 40-79 years), and mature trees (aged 80-119 years). The basins receive approximately 120 inches of average annual precipitation, more than half of which typically falls as snow.

Historic Stream Flow Characteristics

There are two USGS stream measurement gage sites on the Cedar River. The lower gage (USGS 12115000) is located approximately 1.4 miles upstream of Morse Lake. According to USGS gage site information, the contributing area at the gage is 40.5 square miles or 98% of the total basin area. Mean discharge is reported as 260 cfs. There are two USGS gage sites within the Rex River Basin, one on the mainstem of the Rex (USGS site 12115500) and the other is on a smaller tributary, Boulder Creek. The mainstem gage measures flow from 13.4 square miles or 61% of the total area of the Rex River basin. The USGS reports a mean annual flow at the gage site of 102 cfs. Adding the estimated mean annual of Boulder Creek and using area-based scaling to estimate flow contributed by the remaining 4 square miles downstream of the Rex River gage results in an estimate of mean annual flow for the Rex River at its mouth of 150 cfs.

Mean daily discharge data from USGS gages 12115000 on the Cedar and 12115500 on the Rex have been used to develop monthly exceedance curves as shown in figures H1 and H2. For purposes of this study, the seasonal pattern of flows on the Rex River gage site is essentially similar to the Cedar River except at a smaller scale related to different drainage areas measured by each gage site. As illustrated by median and higher flow lines in Figure H1, the annual hydrograph of the Cedar River exhibits a double peak that is characteristic of streams influenced both by rain storms and snow melt. Typically, flows rise from their lowest levels at summer's end as autumn rains begin. Winter flows often reflect a combination of runoff from rainfall that is augmented by snowmelt episodes when warm air accompanies frontal storms (so-called "Pineapple Express" events) originating in the south Pacific. The highest mean daily flows of the year occur in May as a result of seasonal snowmelt augmented by spring rain storms.

Variability of Flows by Month of Annual Hydrograph

Flows are most uniform (narrowest range) during August and September which are summer base flow periods. Storms are few and far between and runoff is damped by soil moisture storage which is replenished by high rates of evapo-transpiration. This is a base flow period supplied by residual snowmelt and steady, shallow subsurface discharge to the rivers. The onset of autumn rains in October cause freshets that greatly widen the range of likely flows compared to the summer period. Calendar years 1960, 1967, 1975 and 1994 (Figures H3-H6) are just a few examples of the typical onset of the rainy season with an initial October freshet followed by larger storm hydrographs. In some years September storms may bring an earlier freshet and in some years freshets are delayed into November. In drought years freshets are delayed and may not arrive until December as illustrated by calendar years 1952 and 1987 (Figures H7 and H8).

Exceedance Levels of Mean Daily Flow By Month
Cedar River nr Cedar Falls USGS 12115000, DA=40.7 sq mi
(Mean Daily Flow Data 1946-2004)

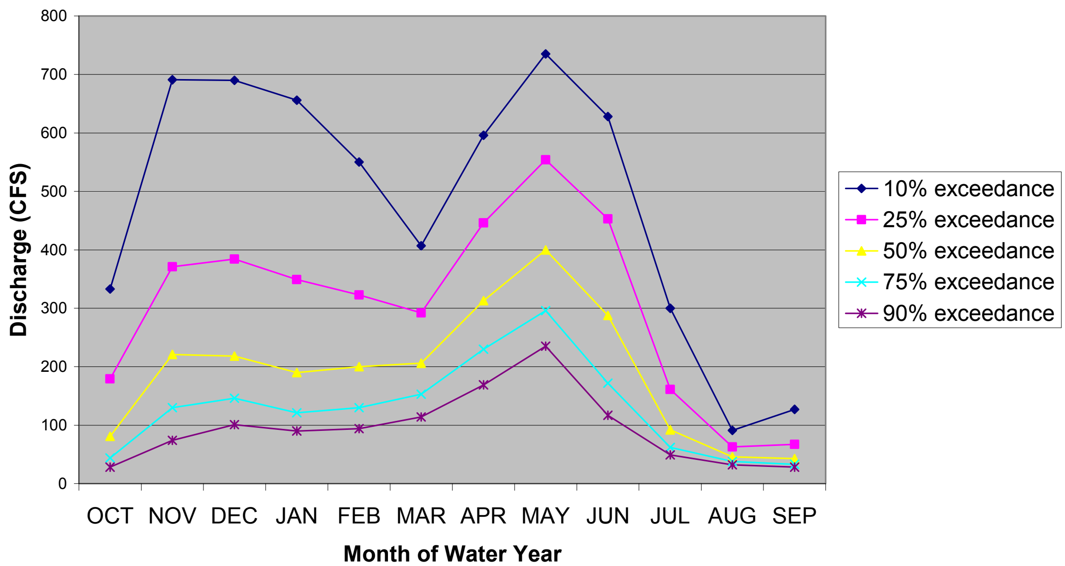


Figure H1

Exceedance Levels of Mean Daily Flow By Month
Rex River nr Cedar Falls USGS 12115500, DA=13.4 sq mi
(Mean Daily Flow Data 1946-2004)

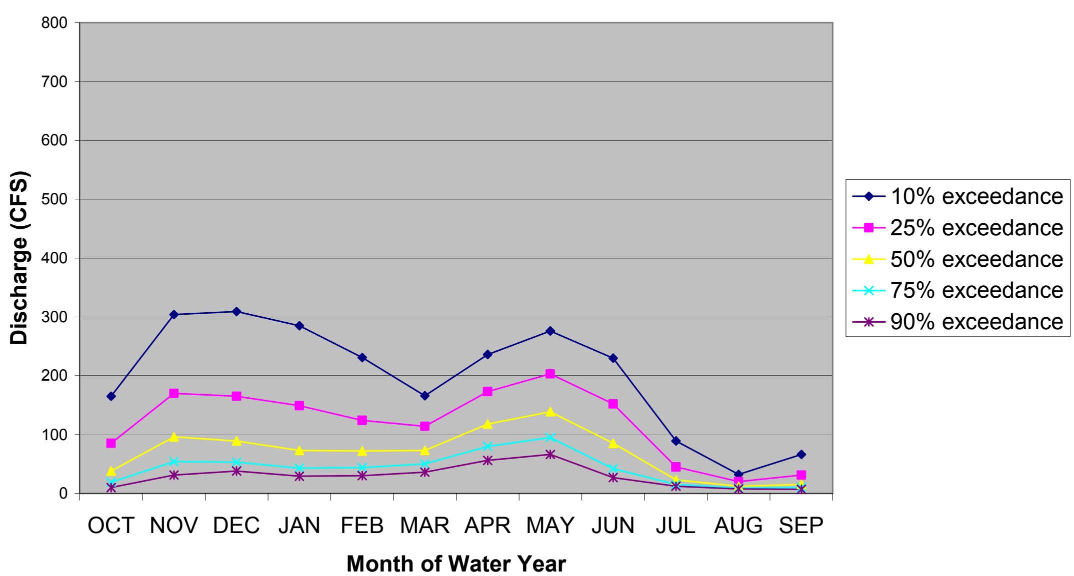


Figure H2

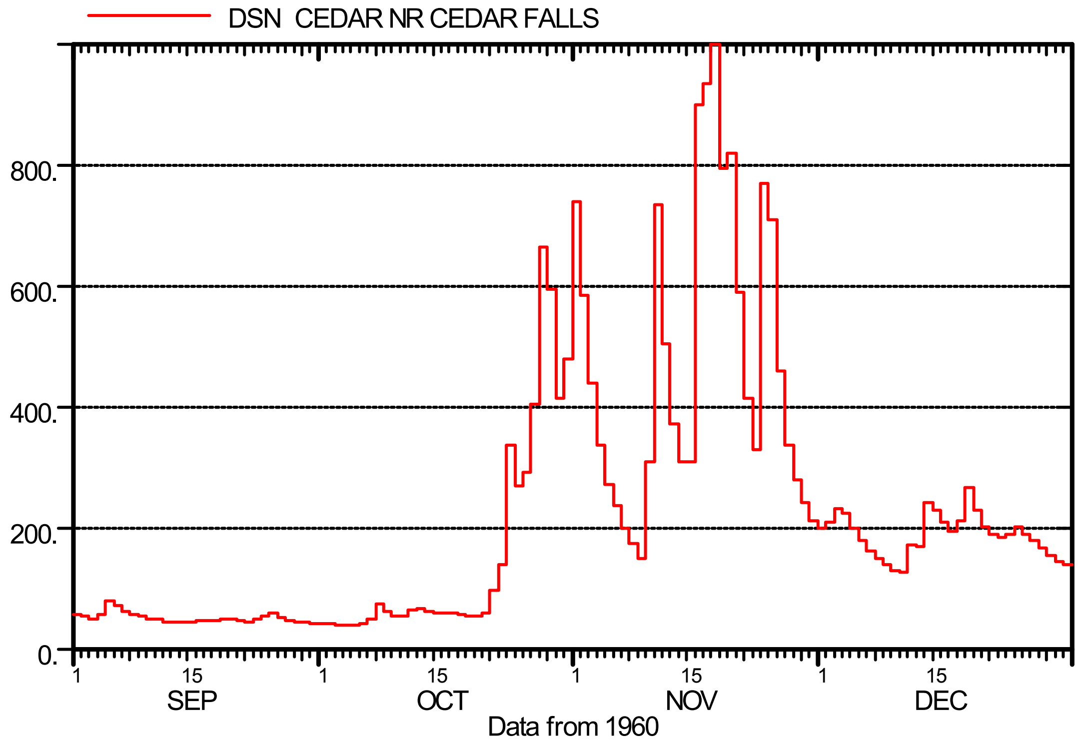


Figure H3

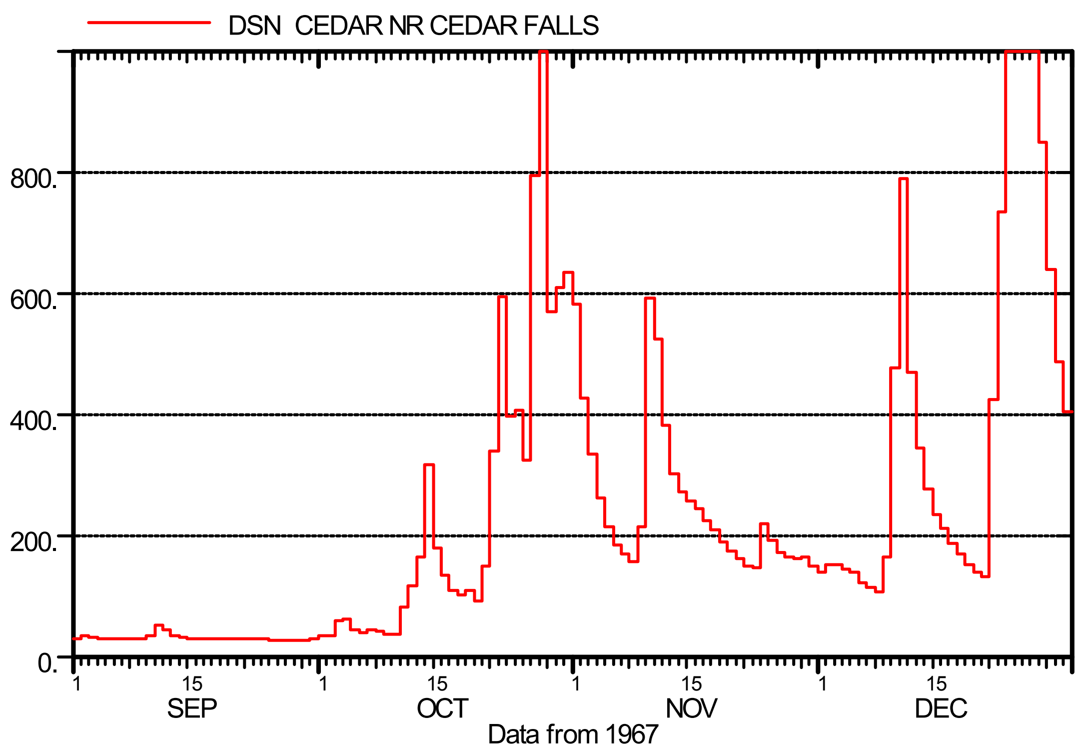


Figure H4

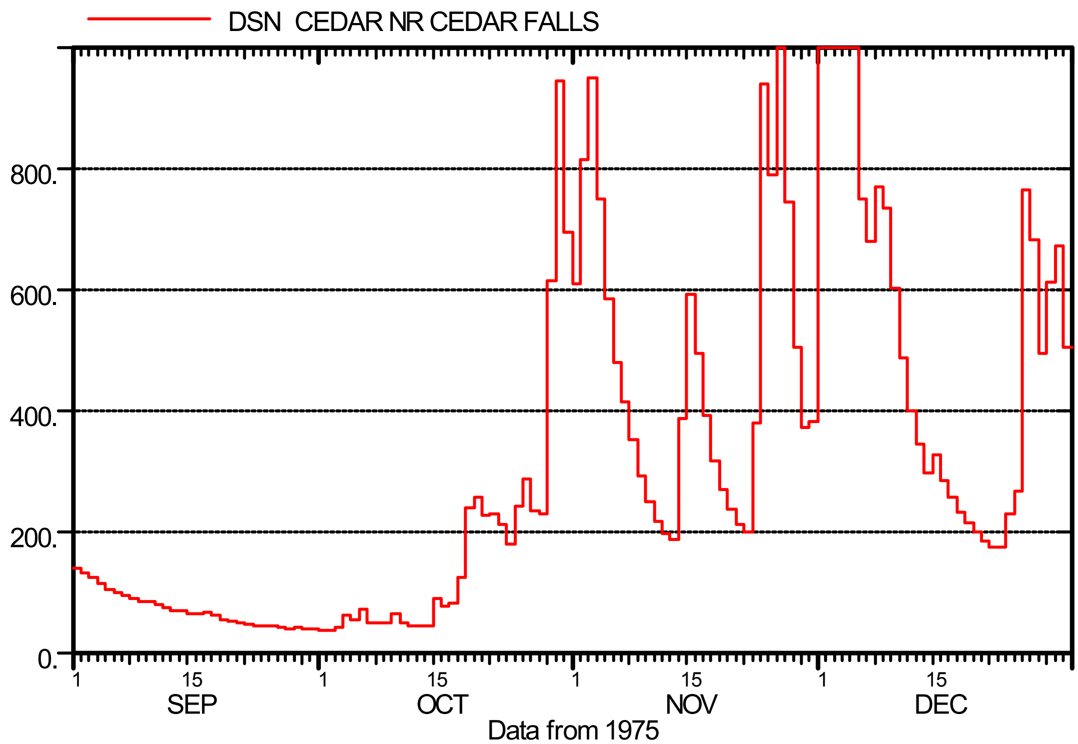


Figure H5

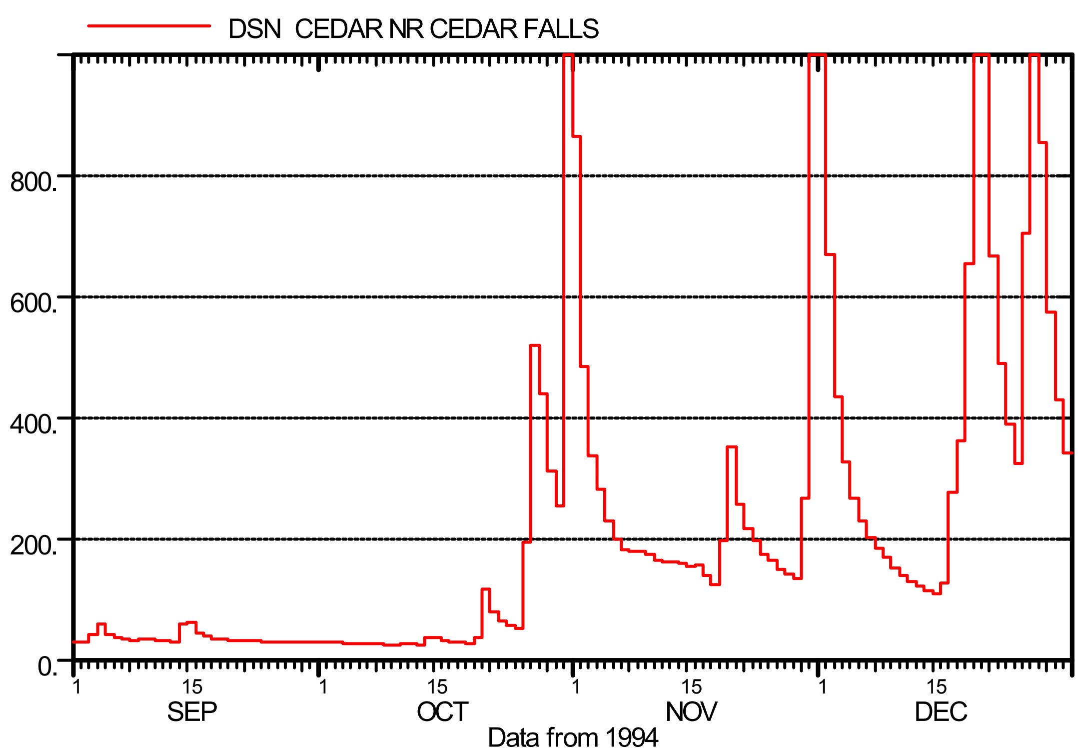


Figure H6

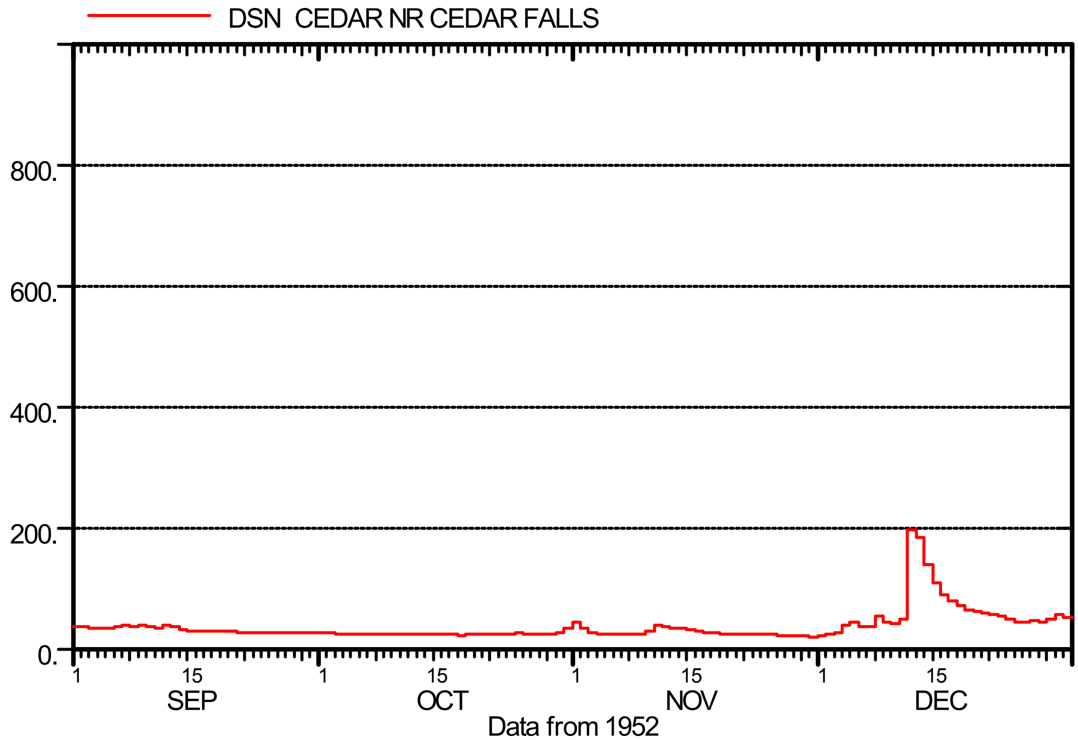


Figure H7

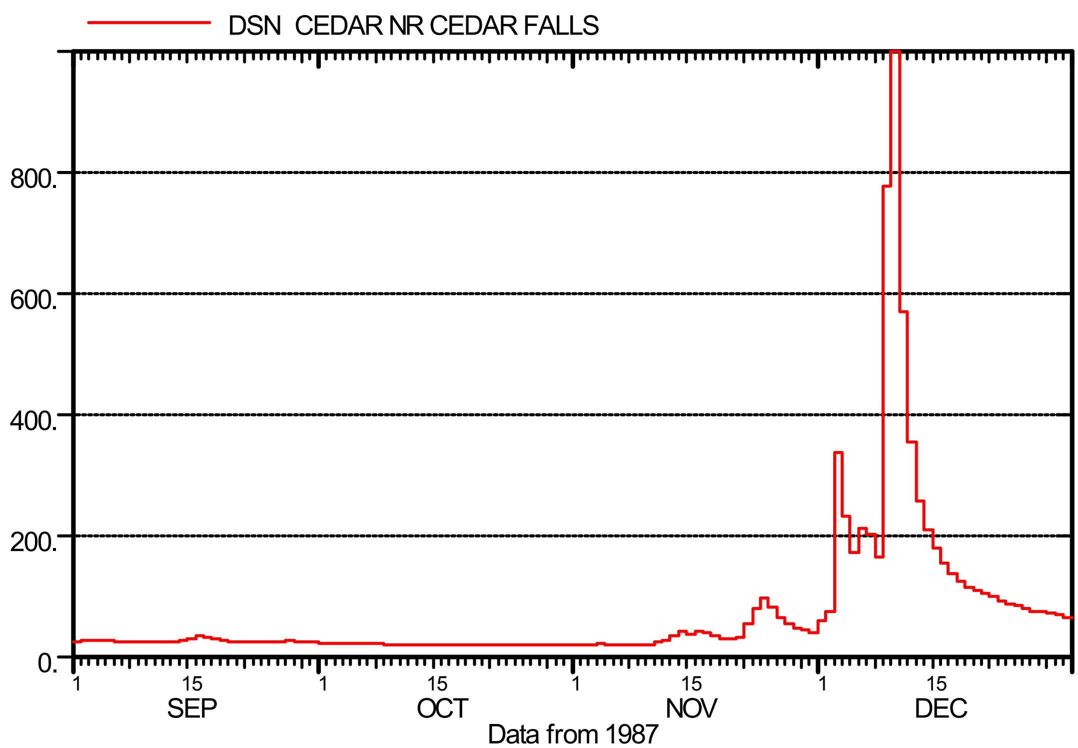


Figure H8

Exceedance Probability of Morse Lake Levels by Month

The historical daily water surface elevations of Morse Lake were analyzed to determine exceedance probabilities of lake levels by month. Figure H9 shows the range of Morse Lake levels that can be expected throughout the year. As indicated by the heavier line representing median levels by month, lake levels have typically varied from a low of 1,544 ft in September to a high of 1,557 ft in May and June. Except in extremely rare droughts, the lowest lake levels occur from September through November. The 5% and 1% lines represent unusually wet conditions caused by high flow events during the fall, winter, and spring while the 95% and 99% lines represent drought conditions. The broken horizontal lines indicate the elevation of the brink on the low-gradient "topsets" of the Cedar and Rex River deltas at the transition to the steeper foreset faces. As the historical data indicate, Morse Lake levels have less than a 1% chance of falling below the topset elevations from February through August.

On the Cedar, the monthly probabilities of the lake falling below the topset brink (1,537 ft) during the months of September, October, November and December are 4.5%, 6.7%, 6.1%, and 2.3% respectively. Percentages on the Rex River are almost identical for the 1,538 ft elevation.

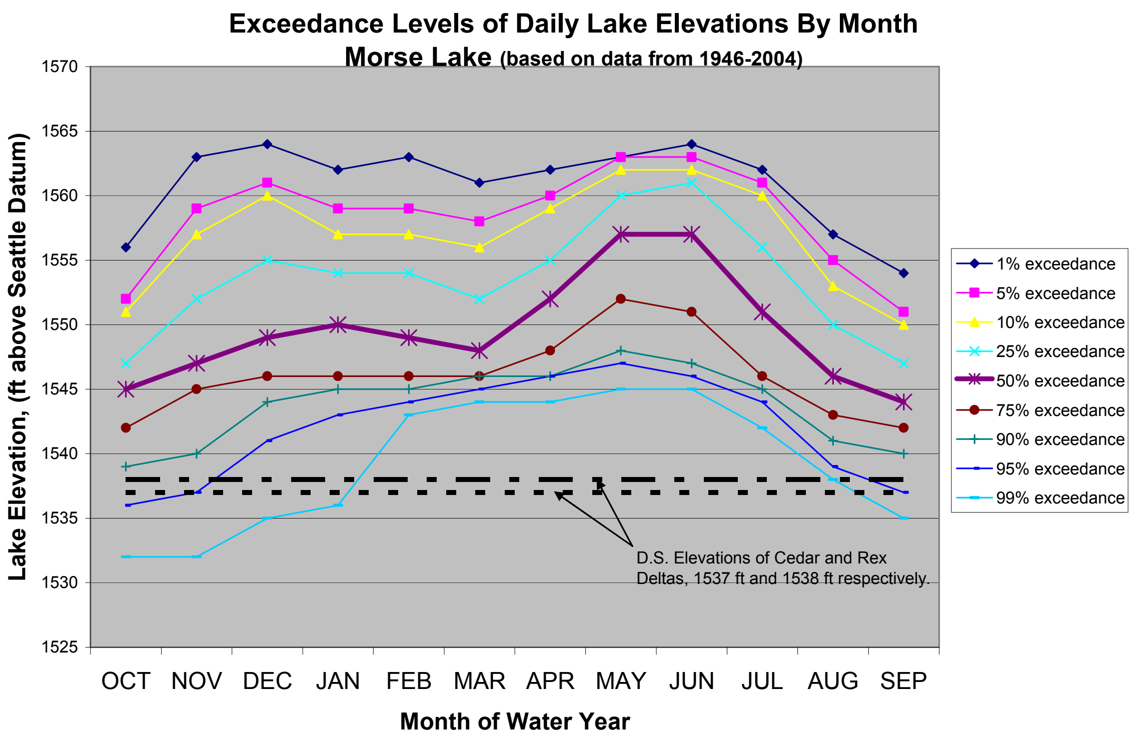


Figure H9

Monthly Exceedance of Discharges at Low Lake Elevations by Month

Fine sediments on the surface of the lower topset and foreset, are likely to erode at even small discharges when the Morse Lake is drawn down to levels that fully expose the topset. Under existing conditions, in the unusual circumstance that the topset is fully exposed by a low lake level, erosion will occur as stream flow transits the brink of the topset and accelerates down the steeper face of the foreset. If a high discharge coincides with an unusually low lake level, erosion can be expected to proceed upstream through nickpoint migration unless constrained by a coarse and resistant sediment armor layer. In order to provide a basis for judging the frequency and intensity of historic channel erosion events, a joint probability analysis of low reservoir levels and Cedar and Rex River discharges was undertaken.

Figures H10 and H11 show the probability of exceeding a range of discharge levels when Chester Morse Lake is less than elevation 1,538 ft (Seattle datum). This is approximately the minimum topset level for either stream delta. Noting that the mean annual discharge is 260 cfs for the Cedar and 102 cfs for the Rex, it is apparent from the 100 cfs line on Figure H10 and the 50 cfs line on Figure H11, that there is less than a 1% chance that the mean daily discharge exceeds 50% of the mean annual flow of either stream during any month of the year with either topset fully exposed.

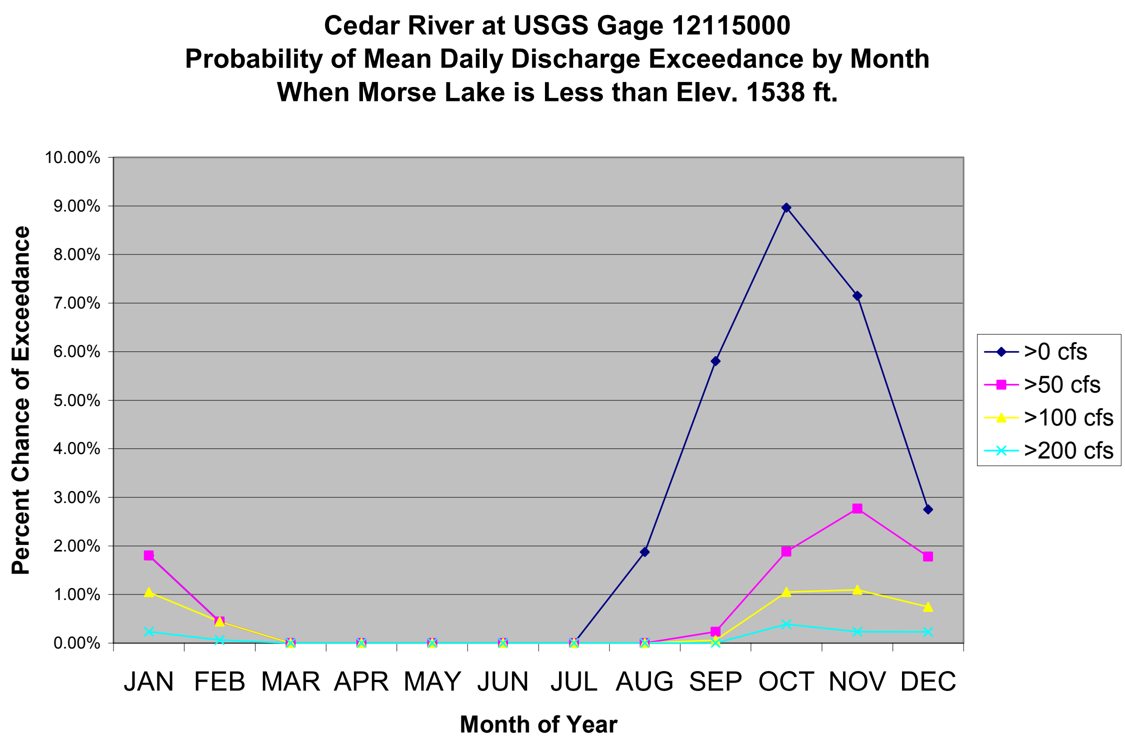


Figure H10

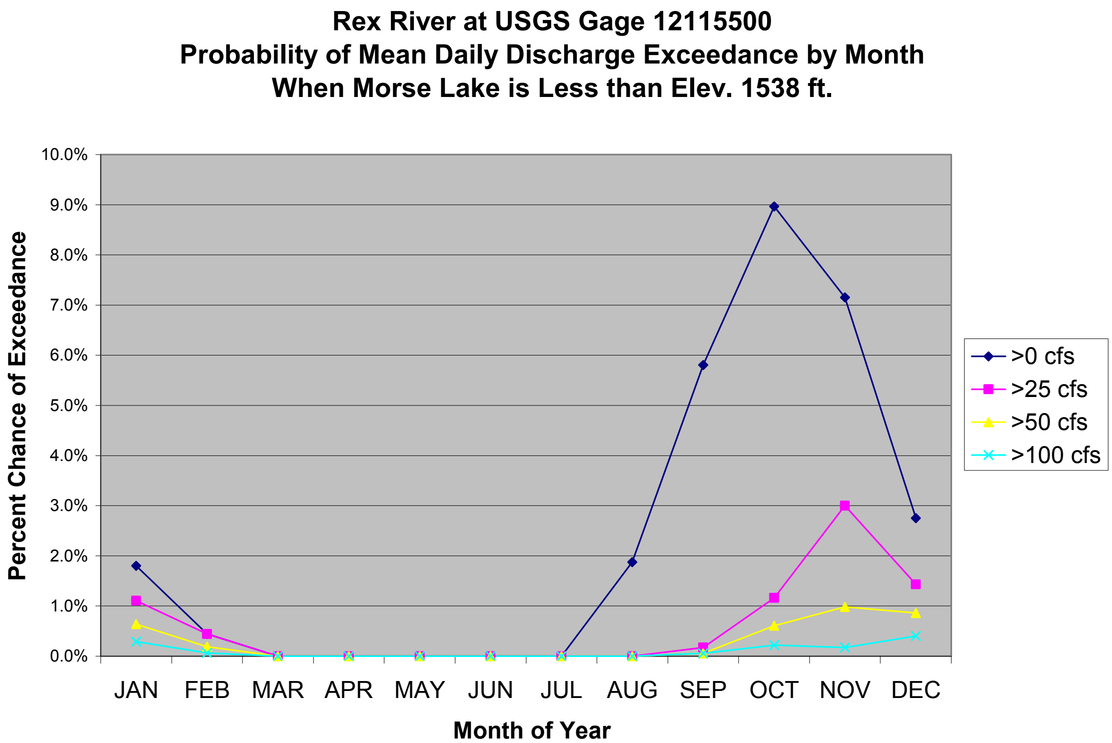


Figure H11

Figures H12 and H13 represent similar discharge exceedance curves for Morse Lake elevations that are lower than 1,542 ft. For reservoir water surface elevations up to this level, discharges exceed 50% of the mean annual flows on each stream less than 5% of the time. The most significant points to note from these curves is that full exposure of the delta topsets has occurred most often during October, but that this has occurred less than 10% of the time on either stream. When full topset exposure has occurred, stream discharges in both rivers were typically well below mean annual flow levels, exceeding 50% of mean annual flow less than 1% of the time.

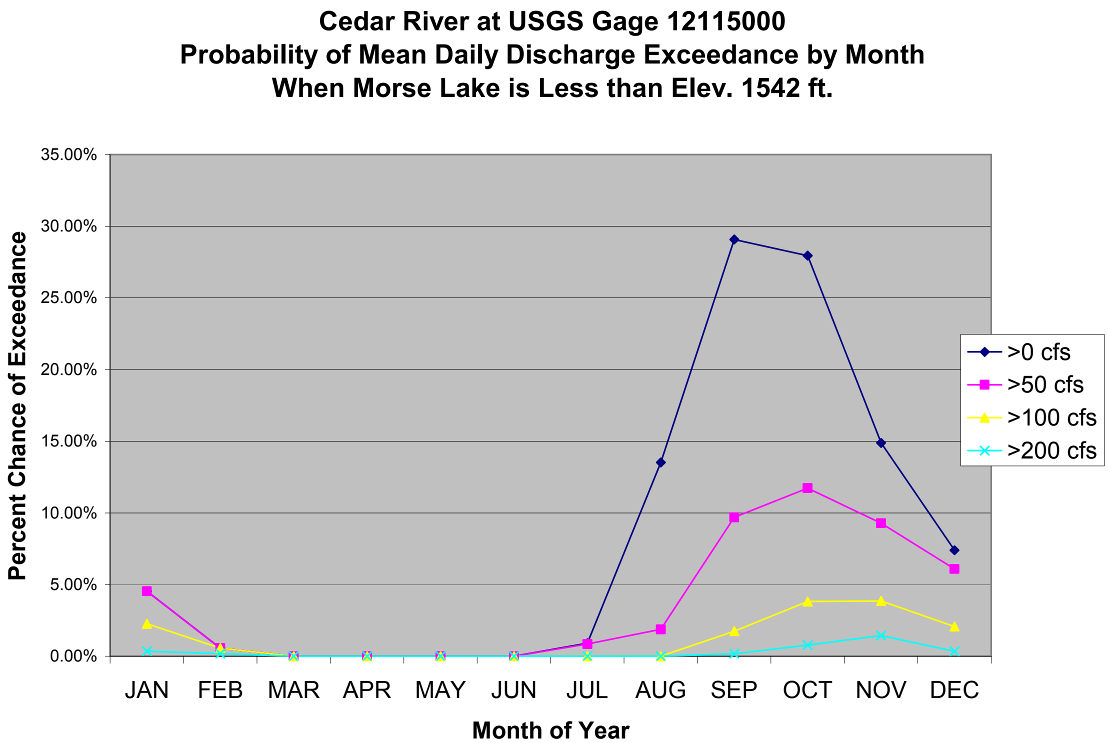


Figure H12

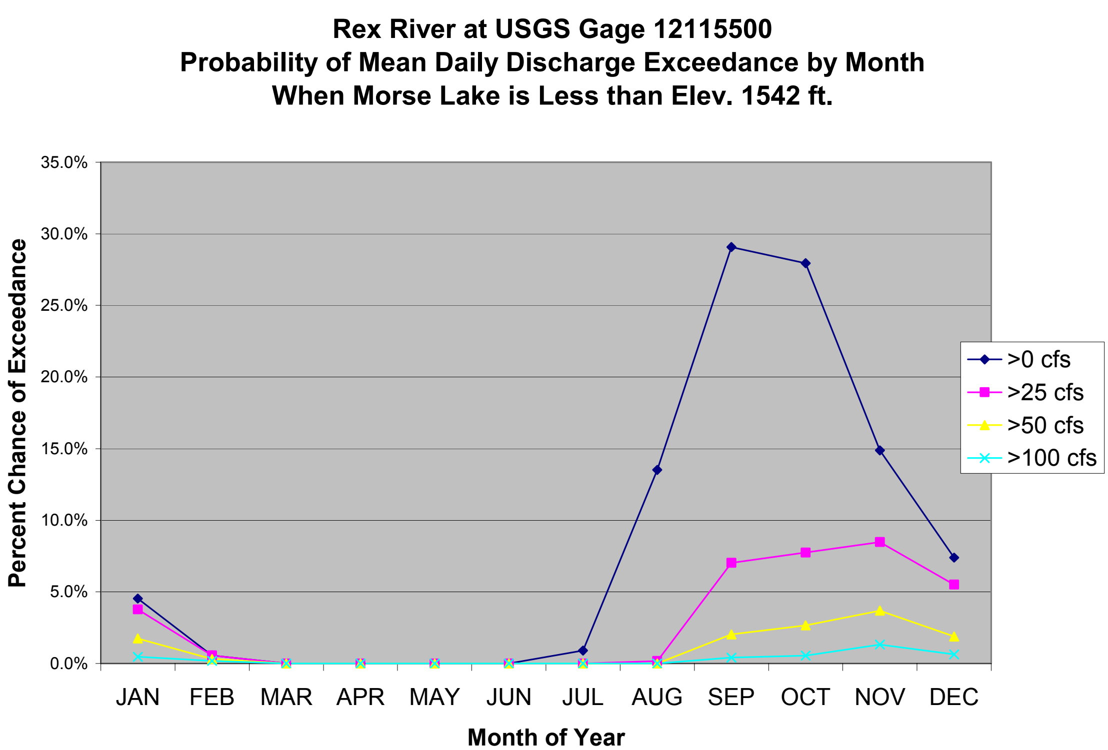


Figure H13

When discharges are greater than mean annual flow, Morse Lake water levels are at least 4.0 ft higher than minimum topset elevations 95% of the time for both deltas. Under existing conditions, the delta topsets and the lower reaches of the Cedar and Rex River channels are very likely to be backwatered during any flood event that exceeds the 1.01 year flood.

Annual Probability and Duration Discharge Exceedance with Low Lake Levels
Tables H1 and H2 provide a more comprehensive summary of the annual frequency and duration of discharge exceedance events when Morse Lake elevations are lower than specified levels. The table is based on daily flow and elevation records spanning a 55 year record from water year 1946 to water year 2004.

The first of the two tables indicates the percentage of years in which upper Cedar River inflows to the lake exceed specified levels concurrently with Morse Lake levels less than specified levels. As indicated by the >0 cfs column, Morse Lake elevations fall below elevation 1,538 ft in approximately 25% of the years and reading across the <1,538 ft row, inflows exceed 200 cfs in approximately 5.1% of the years or in approximately 3 years of the 55-year record.

The annual probability of occurrence of elevations lower than 1,538 for any inflow discharge (Q > 0. cfs) declines rapidly to 17% for 1,536, 9% for 1,534, and 1.7% (once over the period of record) for 1,532. For an inflow exceedance threshold of 50 cfs, annual probabilities are cut in half. Historically, lake levels have only dropped below 1,532 ft on a single occasion (October and November of calendar year 1952)

The next table represents the average duration of the joint low elevation and discharge exceedance events for years when the joint condition is met. For example looking again at the <1,538 row and the >200 cfs column, the table indicates that the average annual duration of this joint condition is approximately 10 days.

Morse Lake levels have drop below 1,538 ft about once every four years, but discharges have exceeded 200 cfs during those low elevation events in only two years of record. As shown in the second table, the average annual duration of the 200 cfs discharge exceedances was 4 days. Flow events exceeding 200 cfs do not occur with elevations lower than 1,534.

Table H1. Percent of Years with Daily Q Higher and Chester Morse Lake Elevations Lower						
Morse Lake Elevations, ft above COS datum	Cedar River Discharge Exceedance Levels (cfs)					
	>0	>50	>100	>200	>400	>600
<1545	93.2%	89.8%	74.6%	47.5%	23.7%	10.2%
<1540	40.7%	40.7%	23.7%	11.9%	1.7%[1]	0.0%
<1538	25.4%	20.3%	15.3%	5.1%	0.0%	0.0%
<1536	16.9%	6.8%	3.4%	1.7%[1]	0.0%	0.0%
<1534	8.5%	1.7%[1]	0.0%	0.0%	0.0%	0.0%
<1532	1.7%[1]	0.0%	0.0%	0.0%	0.0%	0.0%
<1530	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table H2. Average Days of Duration of Joint Discharge Exceedance with Low Morse Lake Elevations, Cedar River						
Morse Lake Elevations, ft above COS datum	Cedar River Discharge Exceedance Levels (cfs)					
	>0	>50	>100	>200	>400	>600
<1545	77.3	46.2	22.4	9.0	2.8	2.2
<1540	37.4	13.0	8.2	3.0	1.0[1]	0.0
<1538	33.1	11.8	7.1	4.0	0.0	0.0
<1536	25.9	14.8	9.0	3.0	0.0	0.0
<1534	23.4	7.0[1]	0.0	0.0	0.0	0.0
<1532	54.0[1]	0.0	0.0	0.0	0.0	0.0
<1530	0.0	0.0	0.0	0.0	0.0	0.0

[1]One event in record from water year 1946 through water year 2004.

Peak Annual and Channel Forming Flows

The top 10 peak annual discharges over a record spanning 1946 through 2005 all occurred in the months of November and December on the Cedar River and in November, December, and January on the Rex River. During the remainder of the 60 years of record, small peak annual flows have occurred from October through June on both rivers, although the late spring floods tend to be among the smallest of record. Figure H14 shows flood frequency curves for both the Cedar and the Rex rivers. Flood quantiles for both streams are tabulated in Table H3

Table H3. Instantaneous Peak Annual Flood Frequency Curves Log-Pearson III, Bulletin 17B WRC			
Annual Probability of Exceedance	Average Recurrence Interval (years)	Cedar River at USGS 12115000 (cfs)	Rex River at USGS 12115500 (cfs)
99%	1.01	648	414
50%	2	2797	1659
20%	5	4296	2492
10%	10	5272	3027
4%	25	6466	3673
2%	50	7319	4131
1%	100	8142	4571

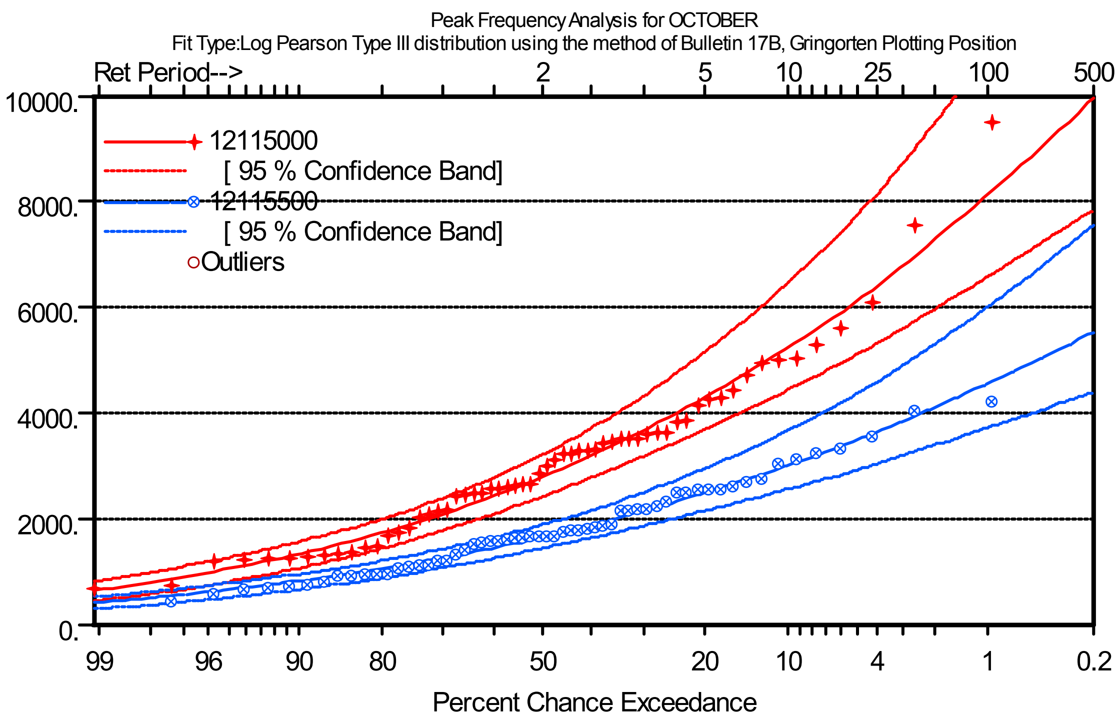


Figure H14

Channel forming or erosive flows that determine the cross-sectional properties and equilibrium slope of an alluvial channel are often defined in terms of a stream's peak annual flood frequency curve. Bankfull discharge is found to be well-approximated by the median (2-year or 50% annual exceedance probability) instantaneous peak. Channel forming flows are typically identified as ranging between the 1.01-year (99% annual exceedance probability) and 2-year peak flow. As shown in Table H3, these flows would range between 648 and 2,797 cfs on the Cedar River and between 414 and 1,659 cfs on the Rex River. As shown in the earlier analysis, *historically, mean daily flows within these ranges have almost never occurred without at least several feet of water covering the deltas of both rivers and likely causing significant backwater to the lower reaches of each stream channel.*

Potential Future Morse Lake Elevation Regime

In order to characterize changes in delta and stream geomorphology that may occur as a result of a project that enables more routine use of Morse Lake dead storage to meet both municipal water supply and lower Cedar River instream flow requirements, SPU hydrologic modeling staff (personal communication, Tom Johanson, SPU) were requested to carry out long term simulations of reservoir inflow and Morse Lake storage and elevation using the Seattle Forecasting Model (SEAFM). SEAFM computes watershed runoff and reservoir inflows from meteorological data, simulates reservoir operations and outflows through low level outlets, power penstocks, and spillways, estimates the behavior of groundwater flow to and from the Cedar moraine and calculates resultant flows in the lower Cedar River on an hourly basis.

Simulations were carried out for a 70-year period extending from water year 1929 through water year 1999 using the "auto-adjust" mode. This mode of simulation involves an iterative simulation of reservoir operations to achieve flow targets downstream at Landsburg in an effort to satisfy instream flow and diversion targets. The following assumptions were employed in the simulations:

1. Landsburg M&I demand ---- 124 mgd annual average diversion per limit in City-MIT agreement scheduled to be effective starting Jan. 1, 2031. Demand pattern based on 1994-2000 average daily pattern. No reductions in M&I demands made for curtailments.

2. Landsburg Minimum Instream Flows ---- Supplements plus High Fall Normal. No switching from normal to critical.

3. Flood Operations-- per fixed rule curve specifying maximum reservoir elevations by month.

4. Minimum Morse Lake Elevations--- Morse Lake allowed to drop as low as 1517 ft (COS datum) to meet specified demand and instream flow targets.

Outputs provided to this project from the SEAFM runs included mean daily discharge for the Cedar and the Rex and daily Morse Lake elevations.

Results and Comparison with Existing Conditions Based on Historical Data

Figure H15 compares the range of Morse Lake levels that can be expected throughout the year assuming a pumping plant and pipeline are used to tap Morse Lake dead storage to meet the demands of instream flow and a 124 mgd average annual diversion with historical lake level conditions. Operation of pump plant that accesses dead storage can make a potentially dramatic difference in the elevation regime of Morse Lake. Whereas under existing conditions the topsets of the deltas are barely exposed 5% of the time in August through November, the probability level is associated with foreset exposures ranging from 2 ft to 20 ft over the same season. Overall the risk of some exposure increases by a factor of three, and the annual probability of the lake being 5 ft below the current delta topset brinks increases from about 2% to 40%.

During the spring, the chance of exposing delta topsets has increased from nil under existing conditions to somewhat more than 1% during the month of March.

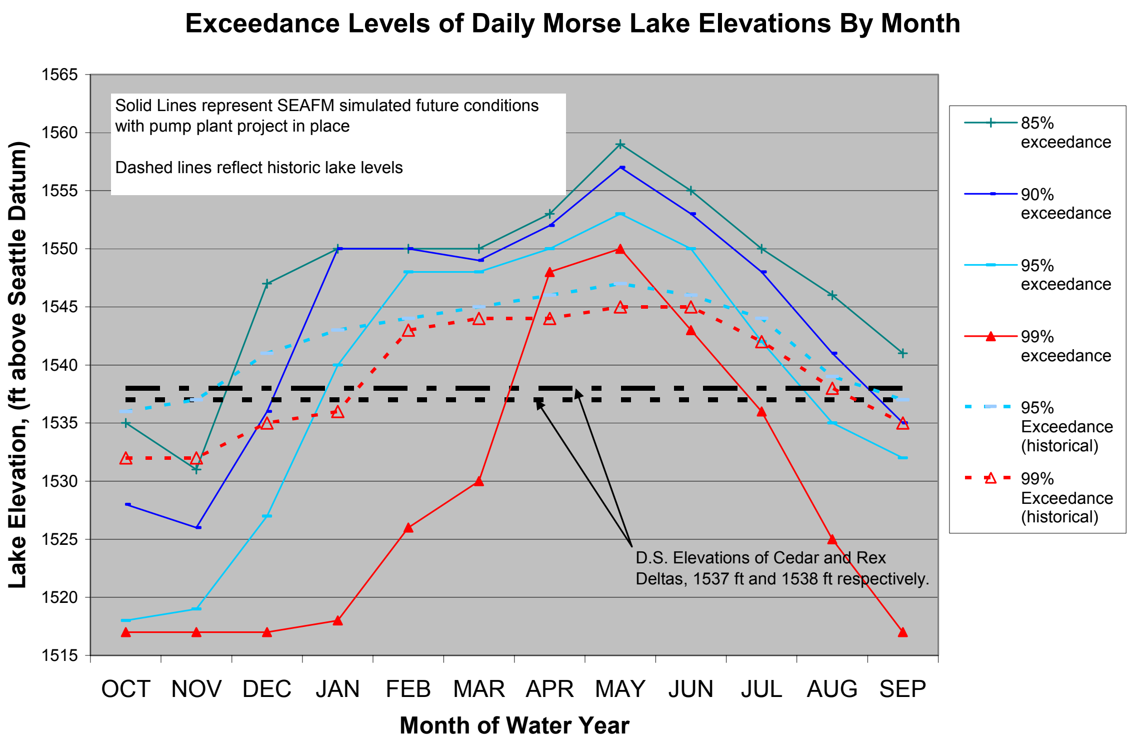


Figure H15

Coincidence of High Flows and Low Lake Levels under Potential Future Conditions
Of more significance than the dramatic increase in the probability of lower Morse Lake levels under the potential future scenario, is the increase in the probability of relatively large stream discharges from either the Rex or the Cedar coinciding with exposed topsets and partially exposed foresets. This is best viewed graphically with simulated lake and stream flow data. Figures H16 –H39 show 24 autumn and winter periods out of a total of 70 years of simulation during which the topsets become fully exposed under the assumed operating scenario described above. Some of these periods of exposure

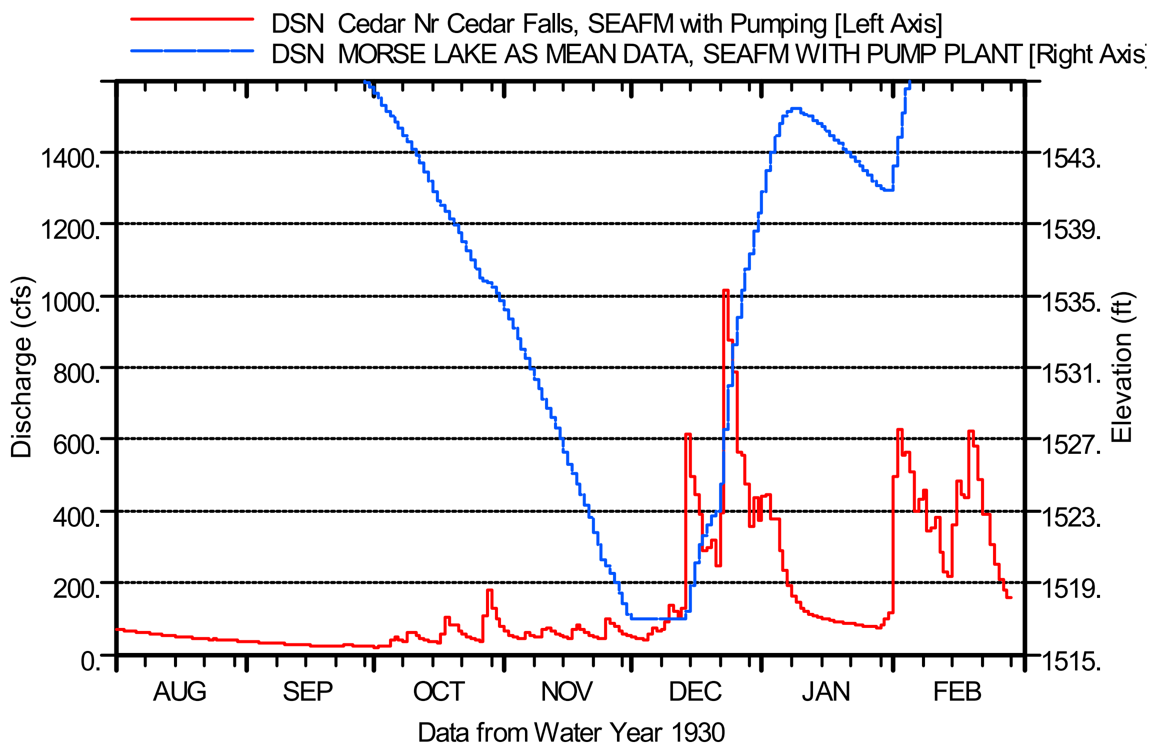
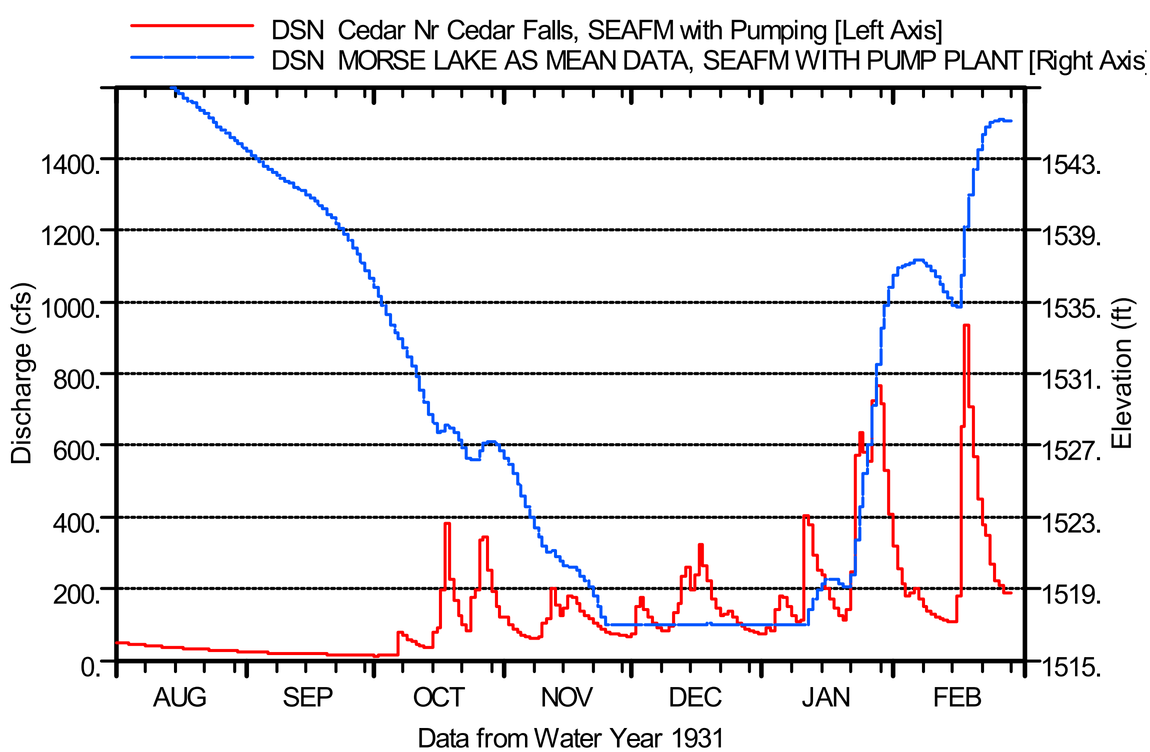


Figure H16



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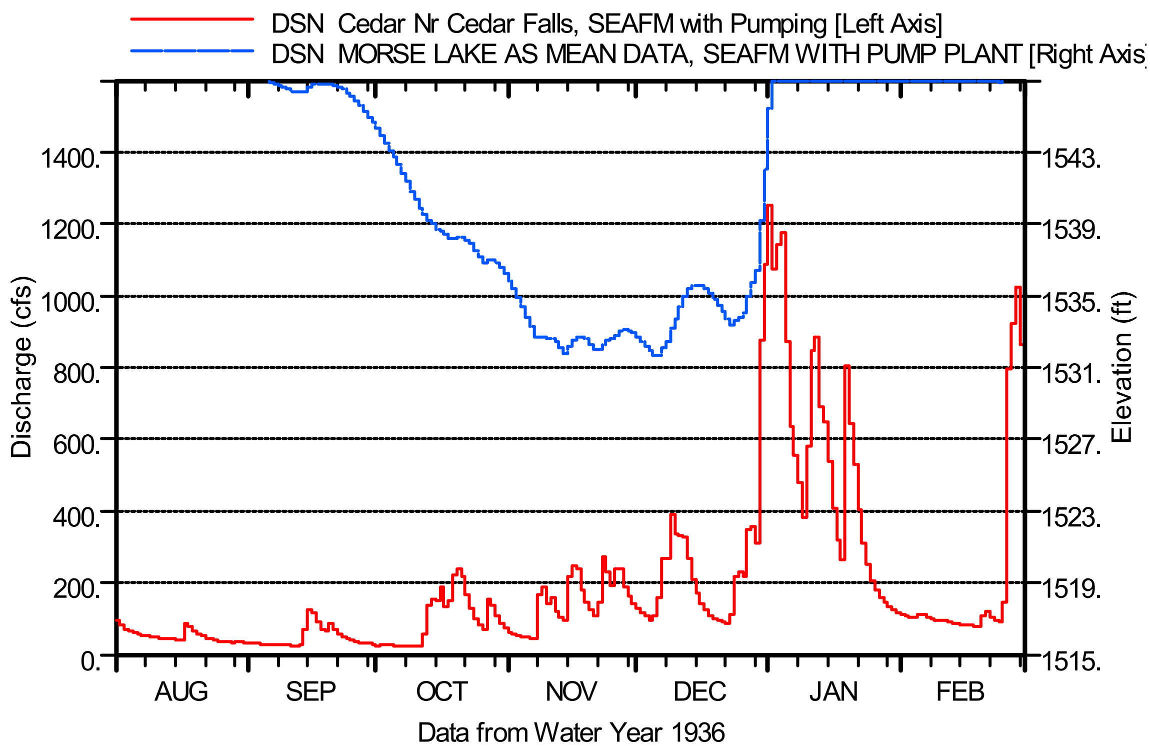

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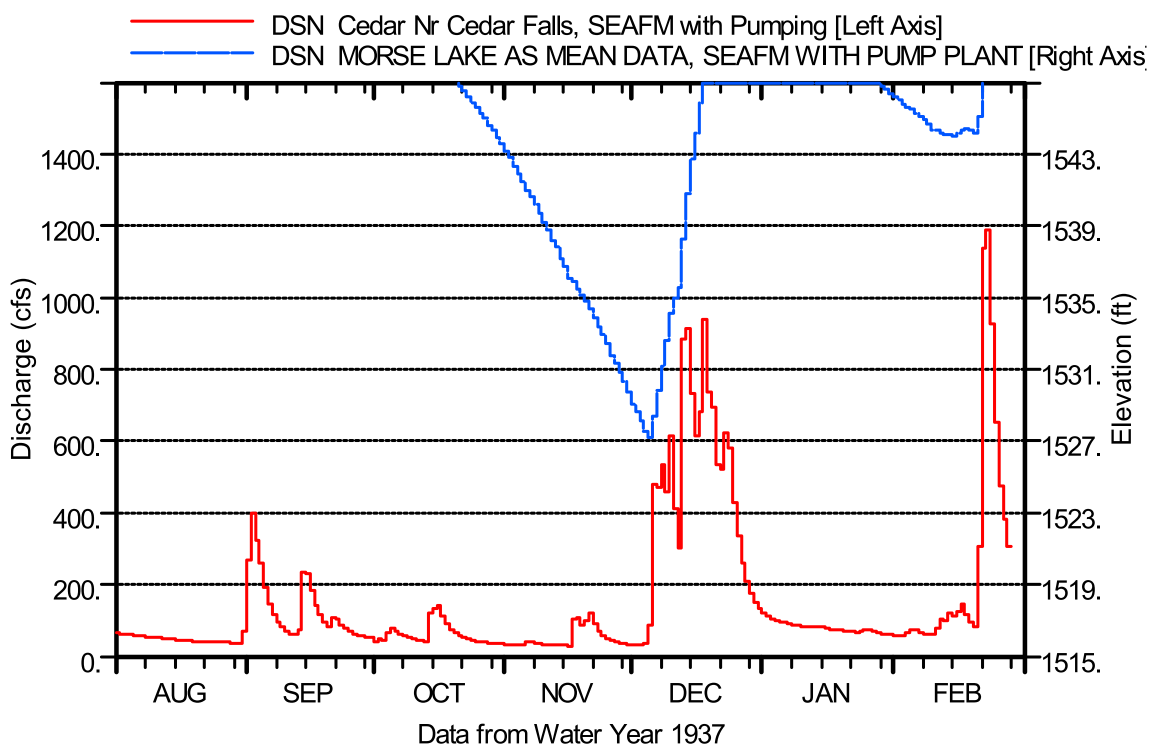

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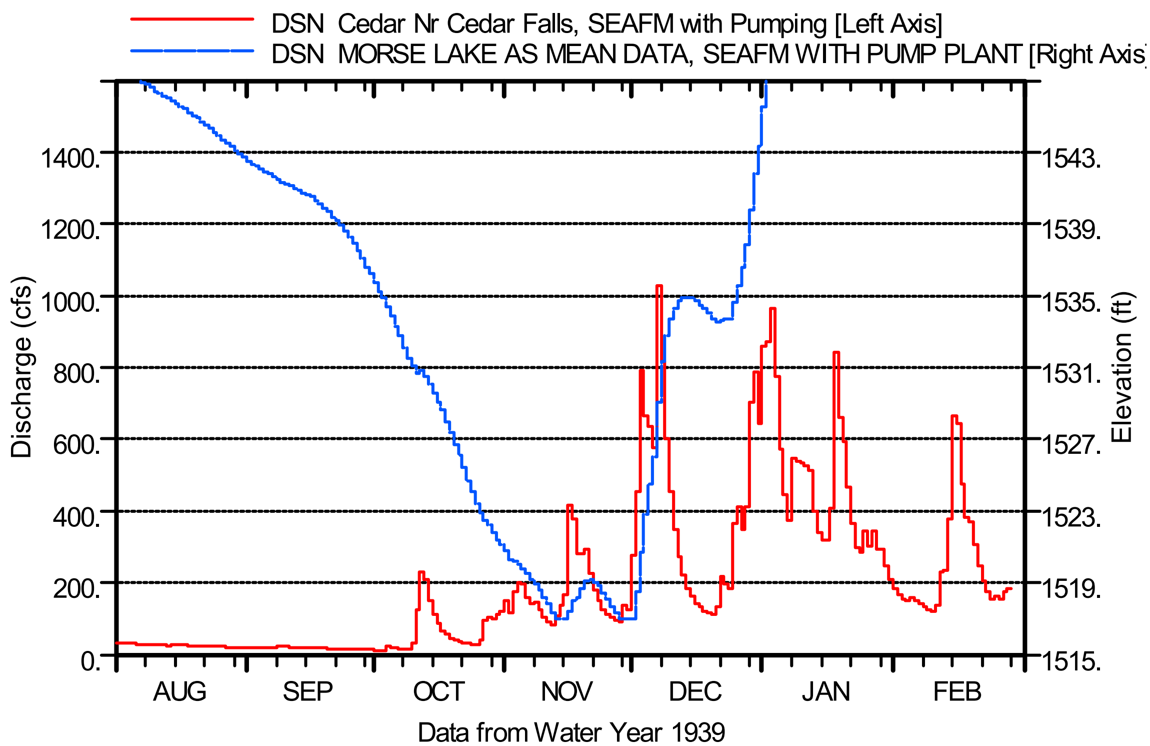

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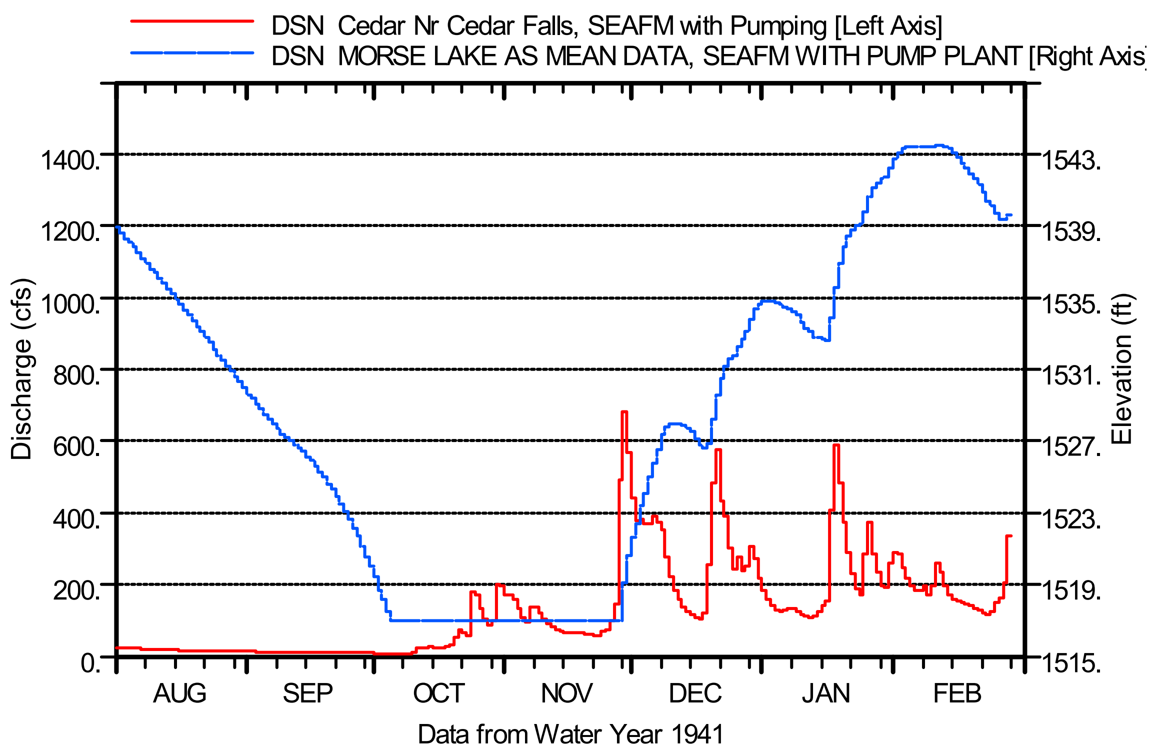

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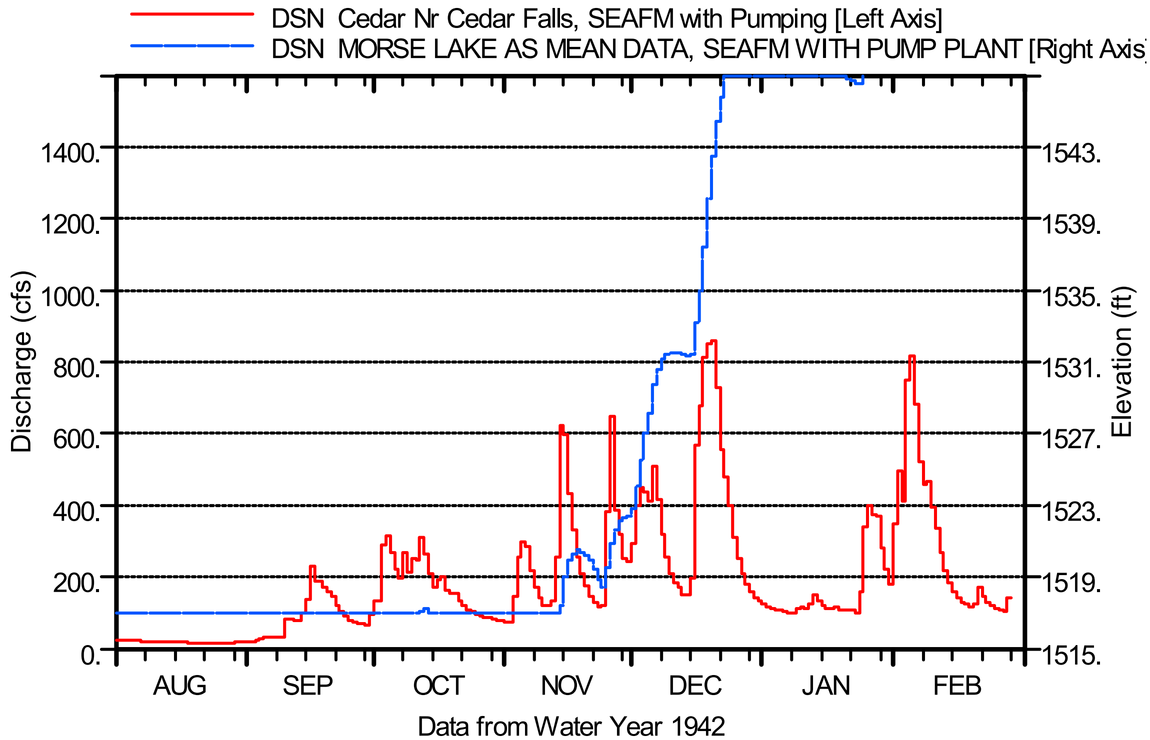

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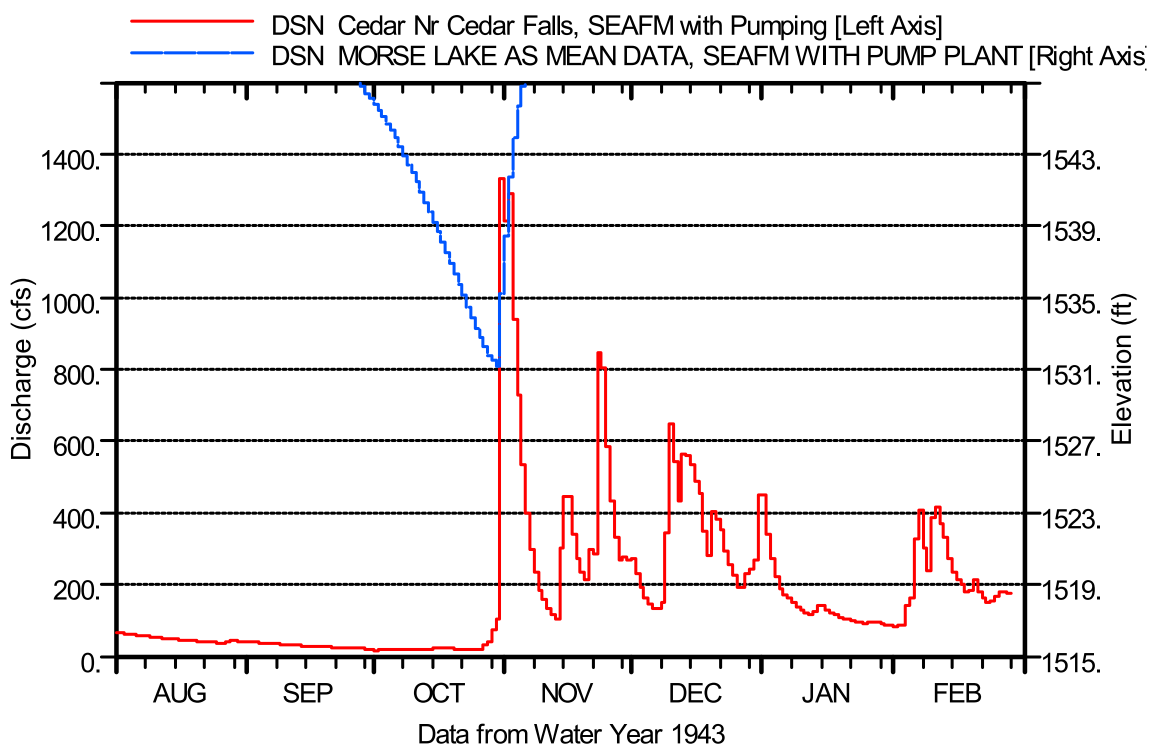

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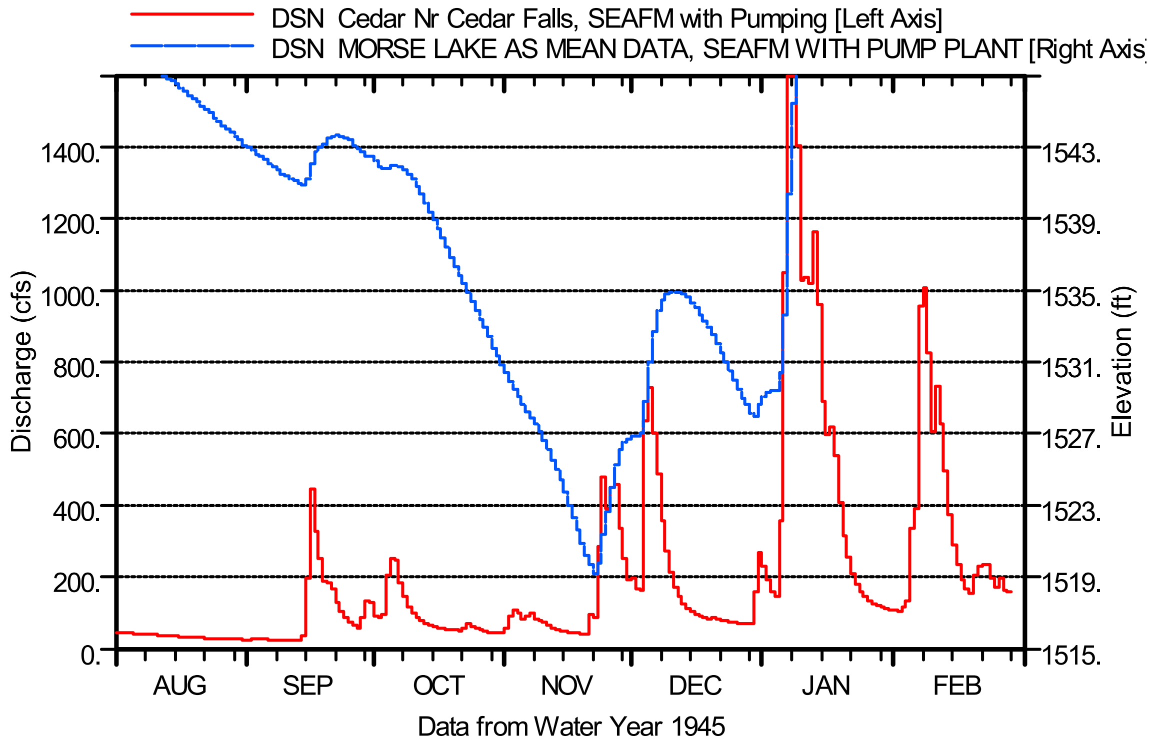

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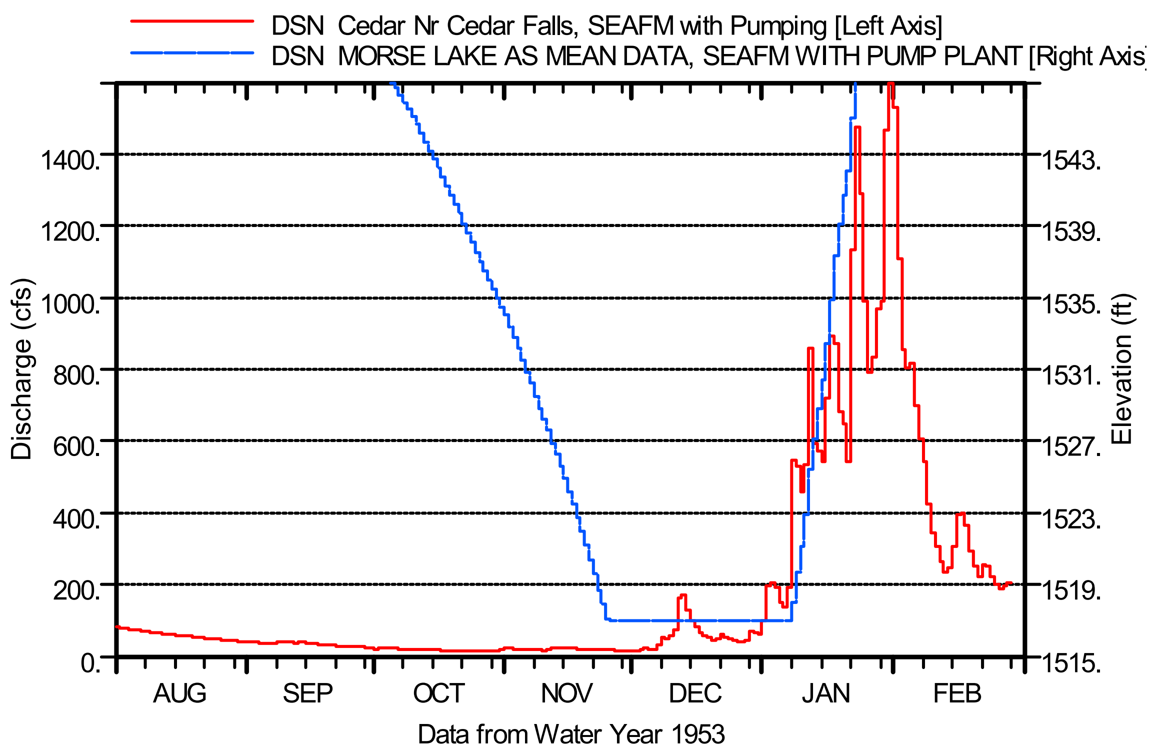

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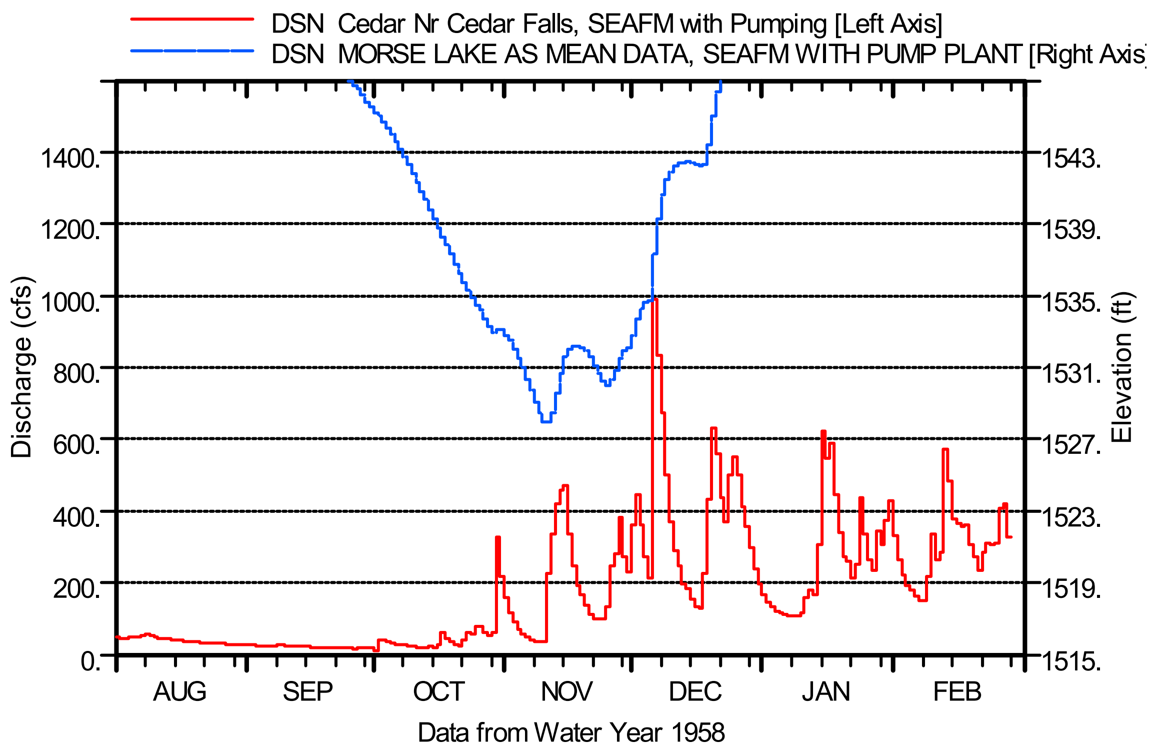

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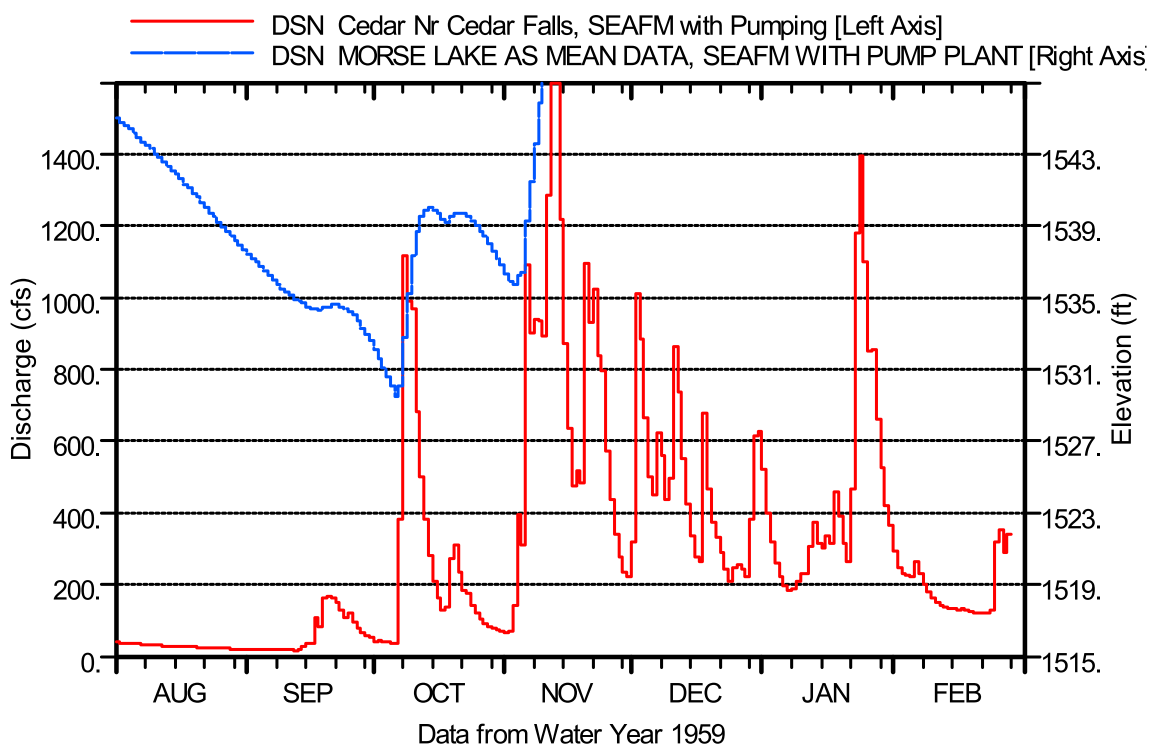

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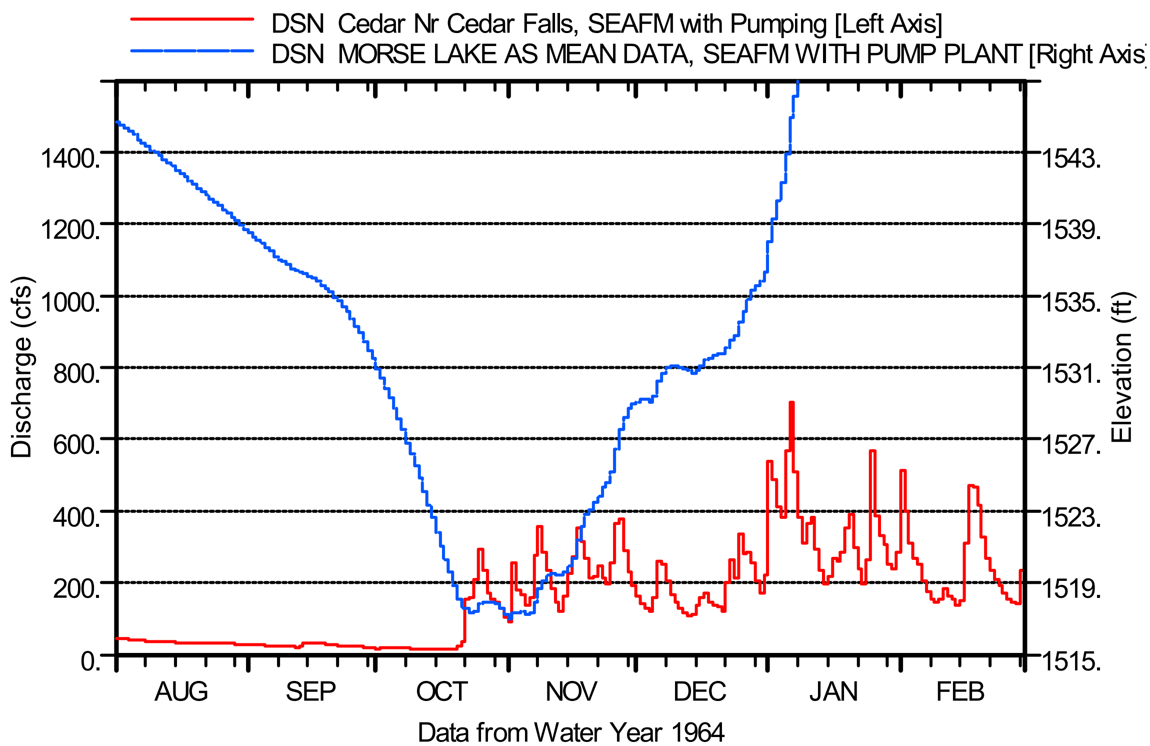

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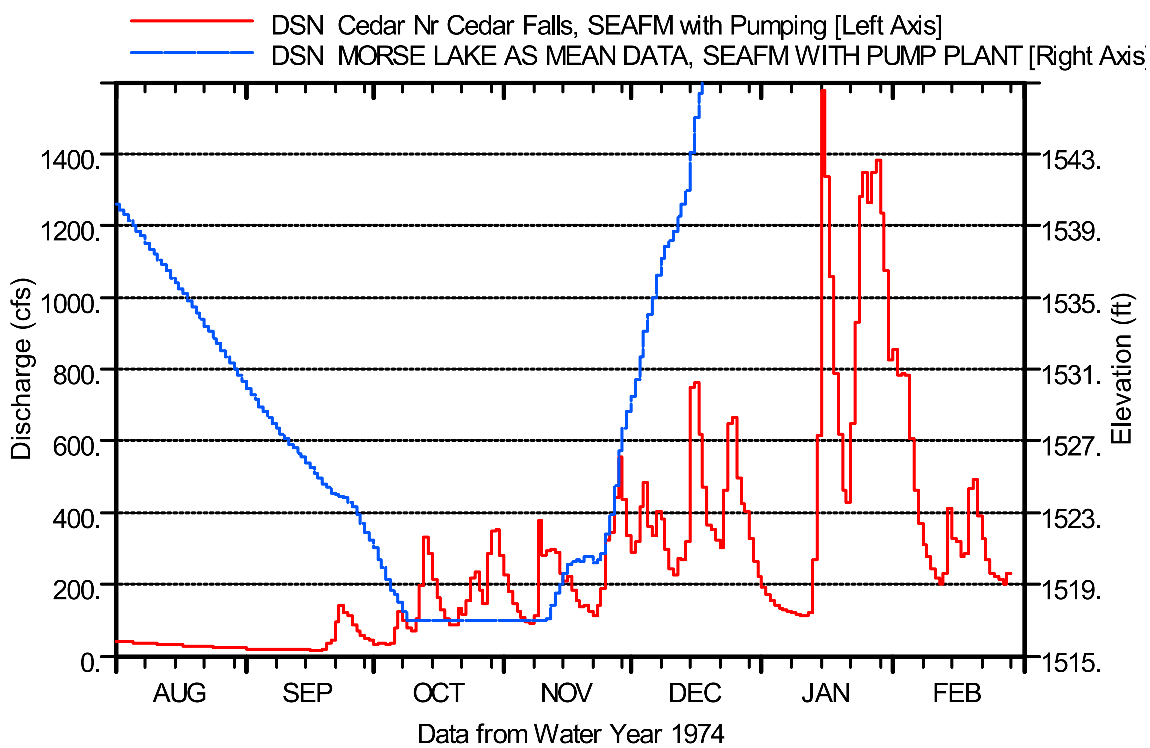

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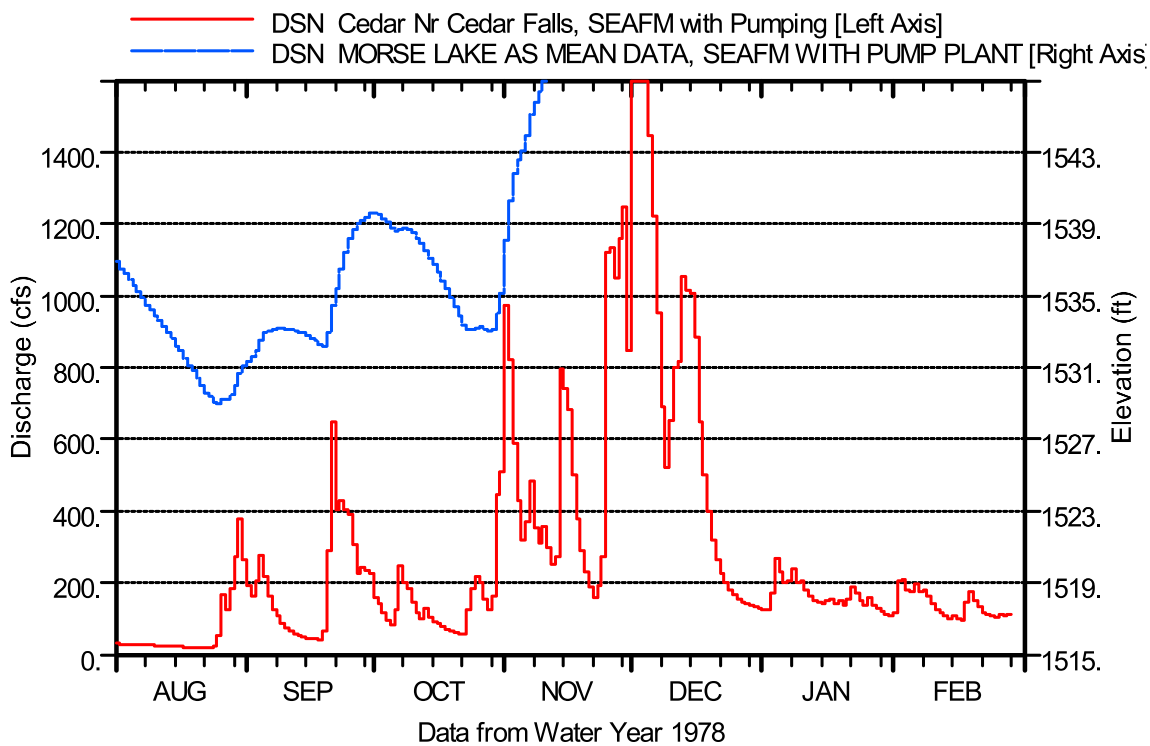

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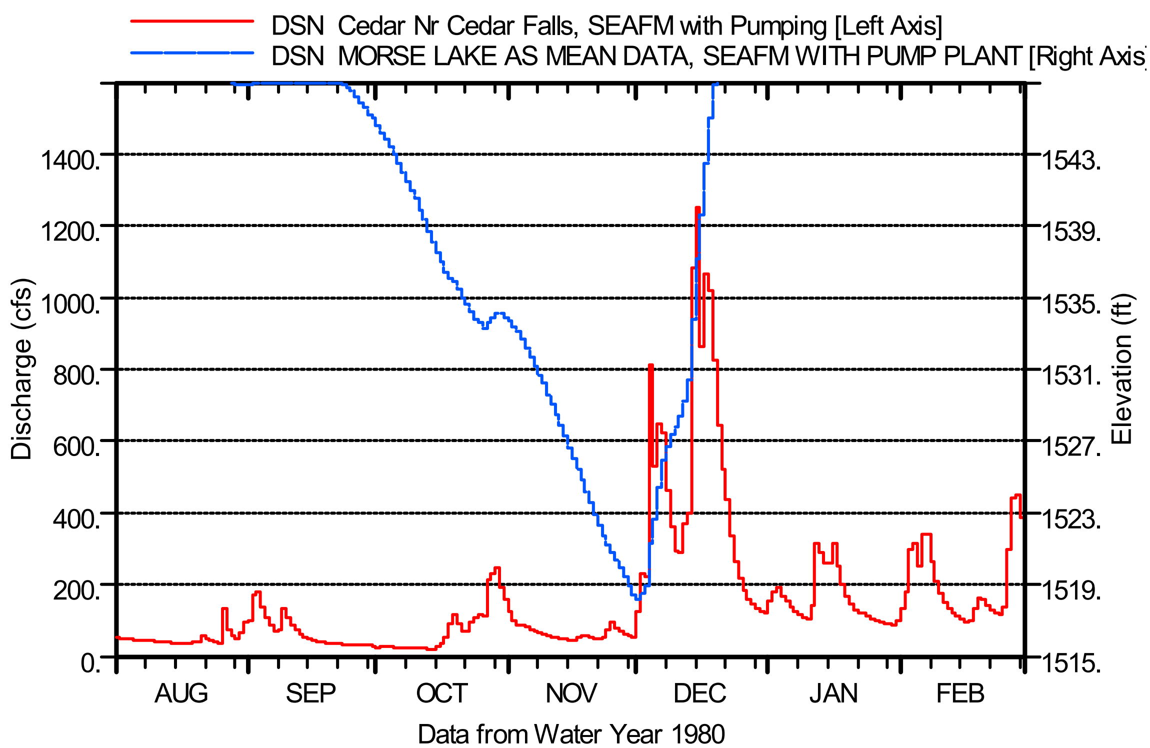

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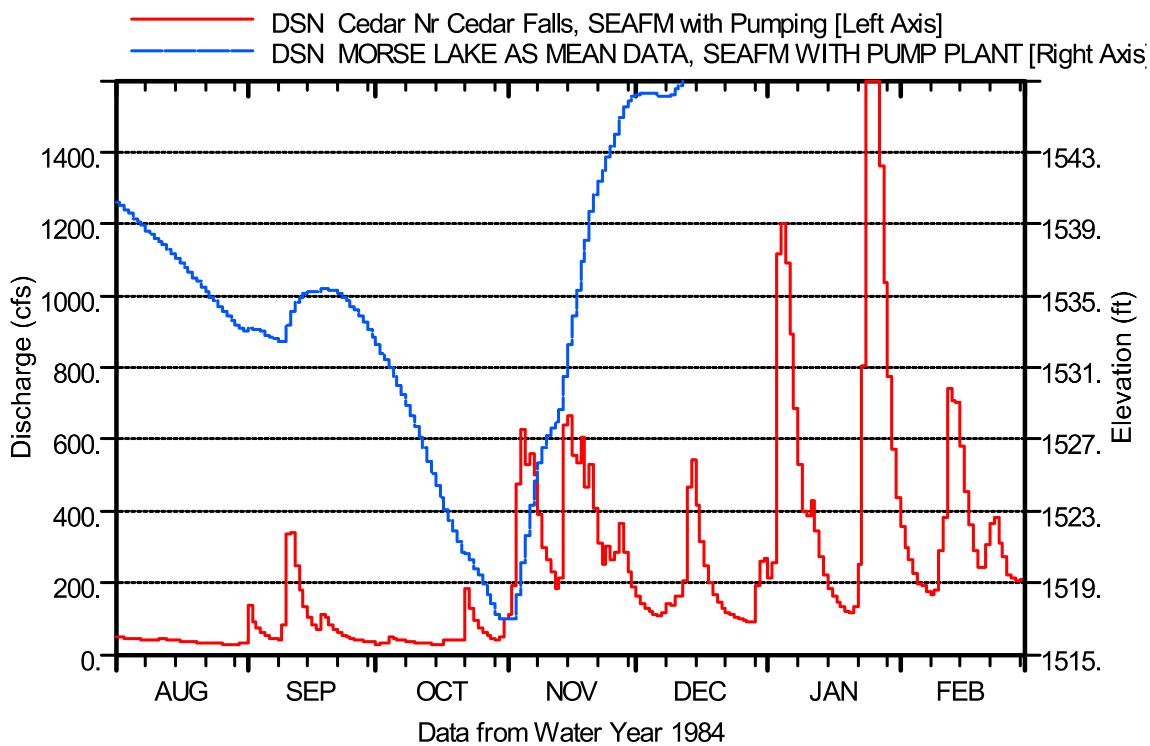

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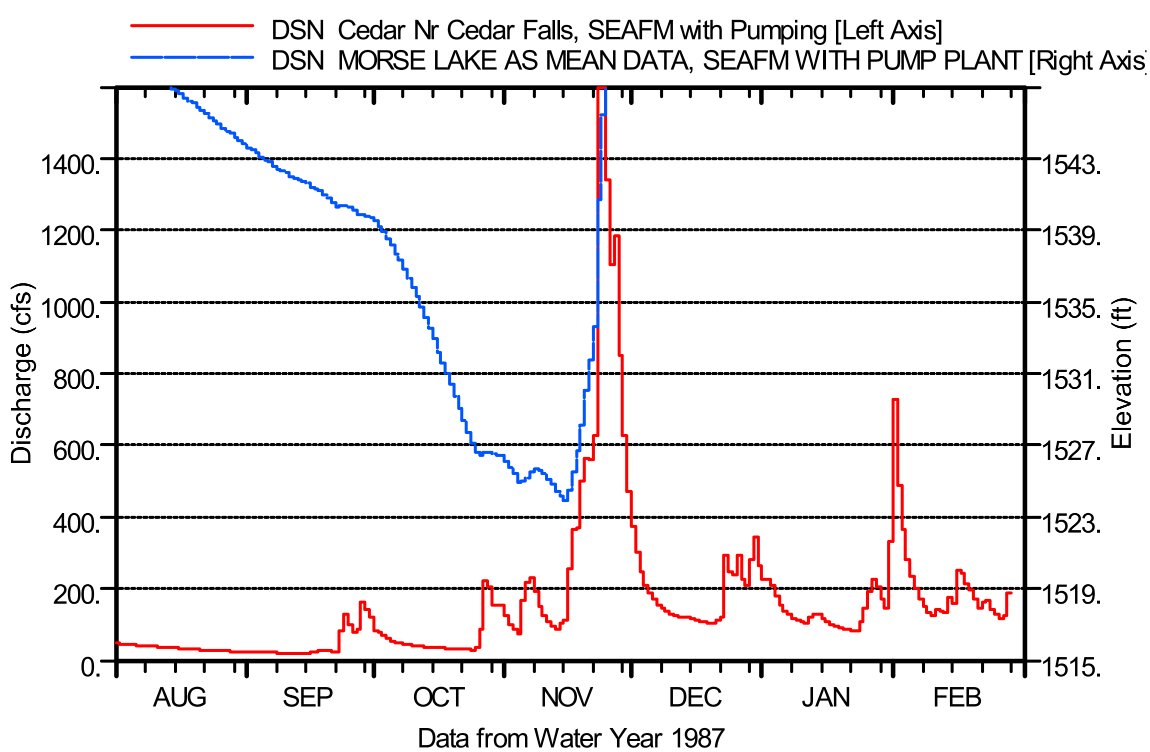

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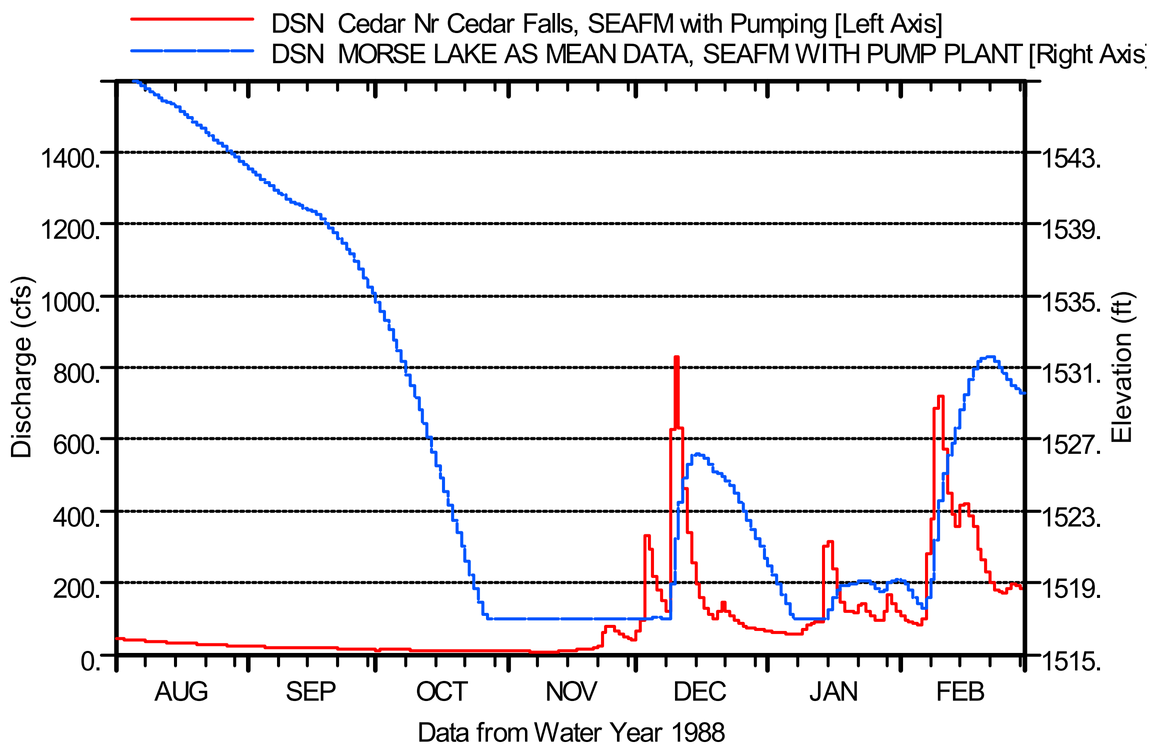

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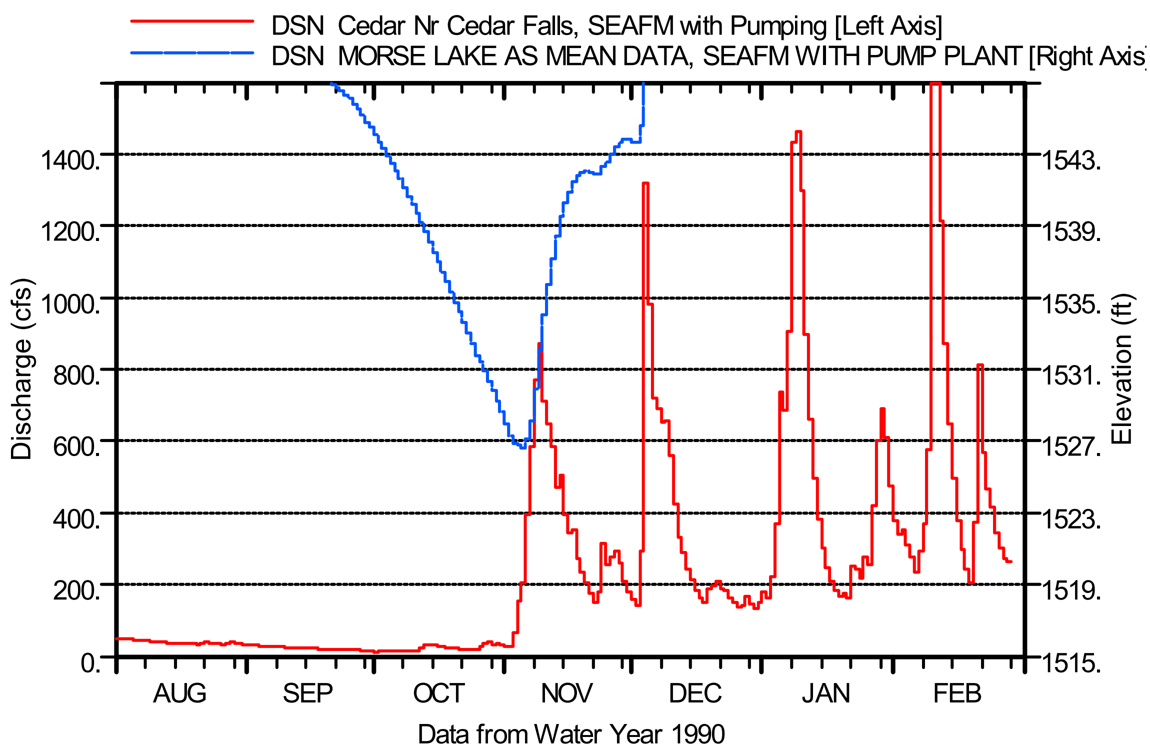

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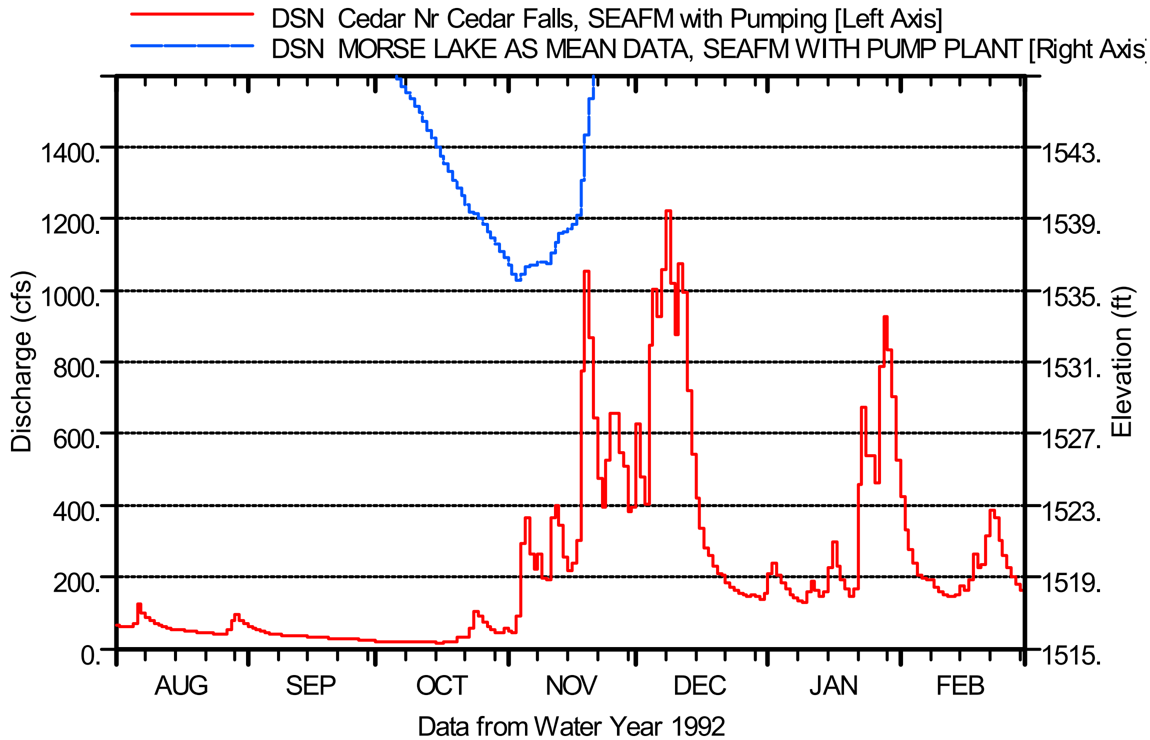

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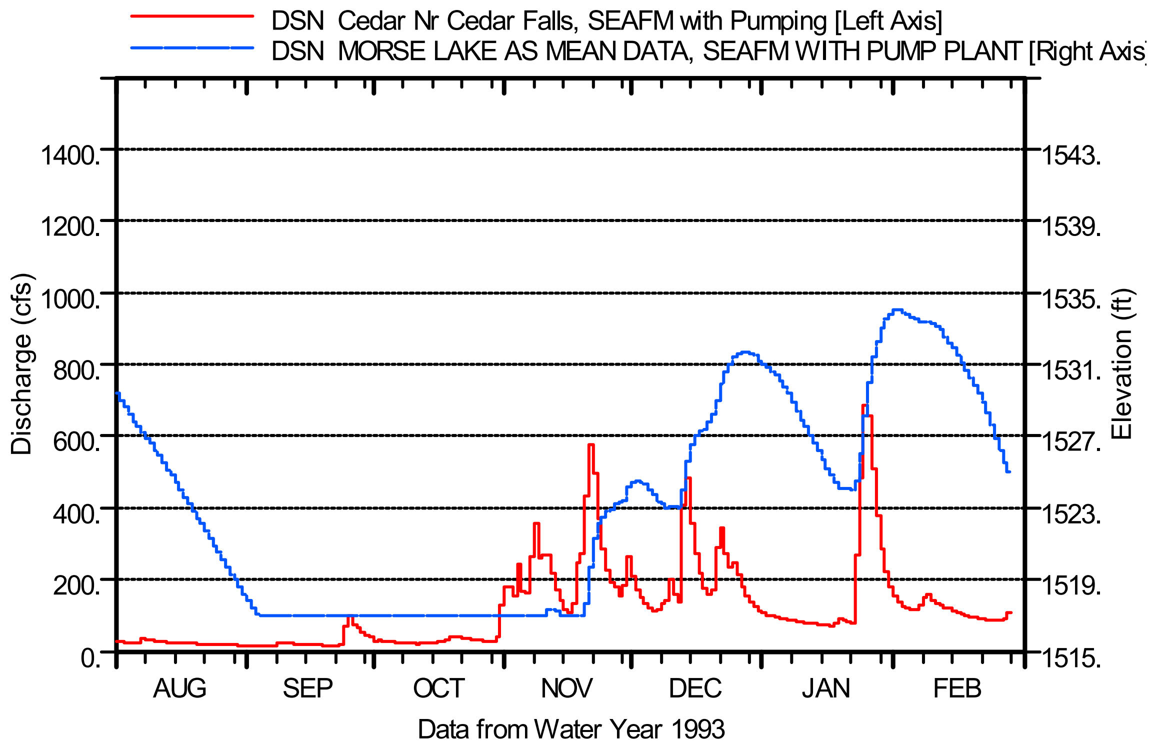

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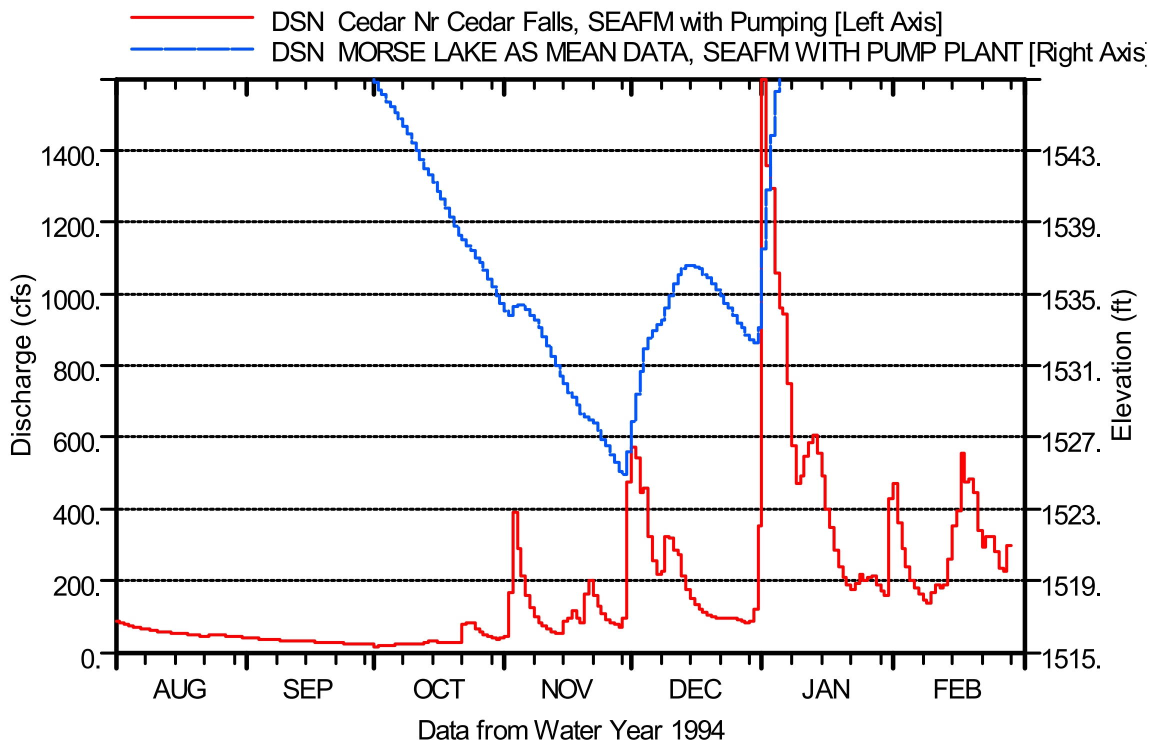

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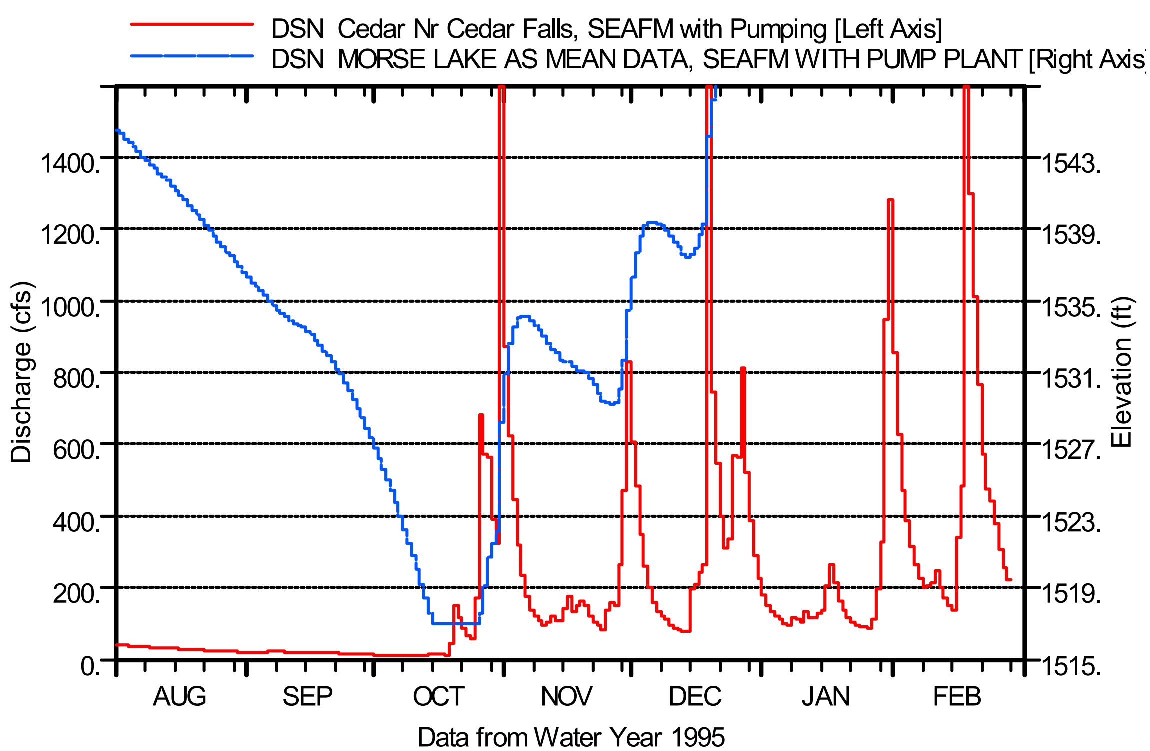


Figure H39

As indicated by Cedar River discharge hydrographs and Morse Lake stage hydrographs shown in these figures, operation of a pump station that accesses dead storage to meet the assumed instream flow and M&I demand at Landsburg on the lower Cedar River, results in deep and sometimes protracted drawdowns of the lake below the existing delta topsets approximately one year in three. These large drawdowns typically occur in the fall to early winter, but in some drought years like water year 1941 may persist into mid-winter.

A statistical summary of the joint occurrence of low Morse Lake levels with discharges in the Cedar River is provided by the Tables H4 and H5.

Table H4. Percent of Years with Daily Q Higher and Chester Morse Lake Elevations Lower

Morse Lake Elevations, ft above COS datum	Cedar River Discharge Exceedance Levels (cfs)						
	>0	>50	>100	>200	>400	>648[1]	>1399[2]
<1545	41.8%	41.8%	41.8%	38.2%	34.5%	29.1%	5.5%
<1540	36.4%	36.4%	36.4%	34.5%	27.3%	20.0%	1.8%
<1538	32.7%	32.7%	32.7%	30.9%	25.5%	18.2%	1.8%
<1536	30.9%	30.9%	30.9%	29.1%	25.5%	16.4%	1.8%
<1534	29.1%	29.1%	29.1%	27.3%	23.6%	16.4%	1.8%
<1532	29.1%	29.1%	29.1%	27.3%	21.8%	12.7%	1.8%
<1530	29.1%	27.3%	27.3%	23.6%	21.8%	7.3%	1.8%
<1525	21.8%	21.8%	21.8%	20.0%	14.5%	1.8%	0.0%
<1520	18.2%	18.2%	18.2%	16.4%	9.1%	1.8%	0.0%

[1] 1.01-year, or 99% instantaneous peak annual exceedance level
[2] 1399 cfs equals 50% of the 2-year, or median instantaneous peak annual exceedance level

Table H4 indicates the percentage of years in which Cedar River inflows exceed specified levels concurrently with Morse Lake levels less than specified levels. As indicated by the >0 cfs column, Morse Lake elevations fall below elevation 1,536 in 30.9% of the years and reading across the <1,536 foot row, inflows exceed 100 cfs in all of those years jointly with reservoir levels that are below the minimum topset elevations of the deltas. This is approximately 10 times as frequent for this discharge exceedance and water level as under historical conditions.

As shown in the flow duration table, an exceedance of 100 cfs with a reservoir level lower than 1,536 with a 31% chance of annual occurrence has an approximate average duration of 33 days. This is 3.7 times the average duration of this condition under existing conditions, which again, has one-tenth the likelihood of occurring annually.

Table H5. Average Days of Duration of Joint Discharge Exceedance with Low Morse Lake Elevations, Cedar River							
Morse Lake Elevations, ft above COS datum	Cedar River Discharge Exceedance Levels (cfs)						
	>0	>50	>100	>200	>400	>648[1]	>1399[2]
<1545	88.9	51.3	36.5	22.1	8.2	3.4	1.7
<1540	78.3	46.9	33.6	18.9	8.0	3.3	2.0
<1538	77.0	46.3	33.3	18.7	7.5	2.9	2.0
<1536	72.9	45.2	32.8	17.9	6.4	2.4	2.0
<1534	67.3	42.6	31.2	16.7	6.1	1.9	1.0
<1532	55.5	34.6	25.3	13.7	5.5	1.7	1.0
<1530	46.0	30.1	21.3	12.6	4.3	1.4	1.0
<1525	41.0	25.0	17.0	8.5	3.3	1.5	0.0
<1520	33.0	19.5	12.9	6.0	1.6	1.0	0.0

[1] 1.01-year, or 99% instantaneous peak annual exceedance level
[2] 1399 cfs equals 50% of the 2-year, or median instantaneous peak annual exceedance level

Coincidence of Rex Discharge Exceedances with Low Morse Lake Levels
Tables H6 and H7 provide data on the joint low reservoir levels and mean daily discharge exceedances for the Rex River that are analogous to the previous two tables for the Cedar River.

Table H6. Percent of Years with Daily Q Higher and Chester Morse Lake Elevations Lower							
Morse Lake Elevations, ft above COS datum	Rex River Discharge Exceedance Levels (cfs)						
	>0	>25	>50	>100	>200	>414[1]	>830[2]
<1545	41.8%	41.8%	41.8%	38.2%	30.9%	10.9%	3.6%
<1540	36.4%	36.4%	36.4%	32.7%	27.3%	7.3%	1.8%
<1538	32.7%	32.7%	32.7%	30.9%	25.5%	5.5%	1.8%
<1536	30.9%	30.9%	30.9%	29.1%	25.5%	5.5%	1.8%
<1534	29.1%	29.1%	29.1%	27.3%	23.6%	5.5%	1.8%
<1532	29.1%	29.1%	29.1%	27.3%	21.8%	1.8%	1.8%
<1530	29.1%	27.3%	27.3%	23.6%	20.0%	1.8%	1.8%
<1525	21.8%	21.8%	21.8%	20.0%	12.7%	0.0%	0.0%
<1520	18.2%	18.2%	18.2%	16.4%	7.3%	0.0%	0.0%

[1] 1.01-year, or 99% instantaneous peak annual exceedance level
[2] 830 cfs equals 50% of the 2-year, or half the median instantaneous peak annual exceedance level

Table H7. Average Days of Duration of Joint Discharge Exceedance with Low -Morse Lake Elevations, Rex River

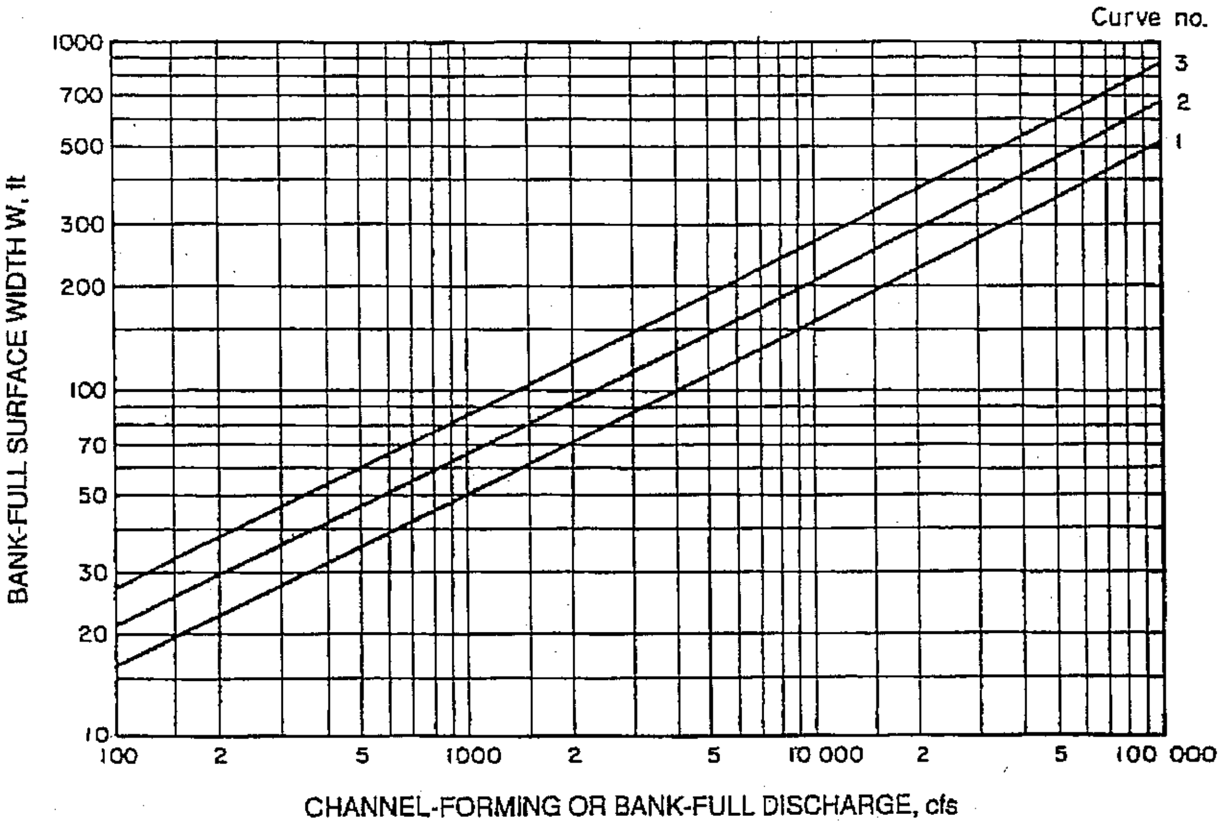
Morse Lake Elevations, ft above COS datum	Rex River Discharge Exceedance Levels (cfs)						
	>0	>25	>50	>100	>200	>414[1]	>830[2]
<1545	88.9	45.7	30.3	17.0	6.2	2.2	1.5
<1540	78.3	42.8	27.6	15.3	5.6	1.8	2.0
<1538	77.0	42.6	27.3	14.7	5.1	1.7	2.0
<1536	72.9	41.7	26.8	13.9	4.4	1.0	1.0
<1534	67.3	39.5	25.7	12.8	4.1	1.0	1.0
<1532	55.5	32.3	21.3	10.8	3.8	1.0	1.0
<1530	46.0	28.1	18.3	9.9	3.3	1.0	1.0
<1525	41.0	22.8	14.1	6.6	3.0	0.0	0.0
<1520	33.0	17.7	10.8	4.6	1.8	0.0	0.0

[1] 1.01-year, or 99% instantaneous peak annual exceedance level

[2] 830 cfs equals 50% of the 2-year, or half the median instantaneous peak annual exceedance level

APPENDIX D

U.S. Army Corps of Engineers Channel Regime Figures

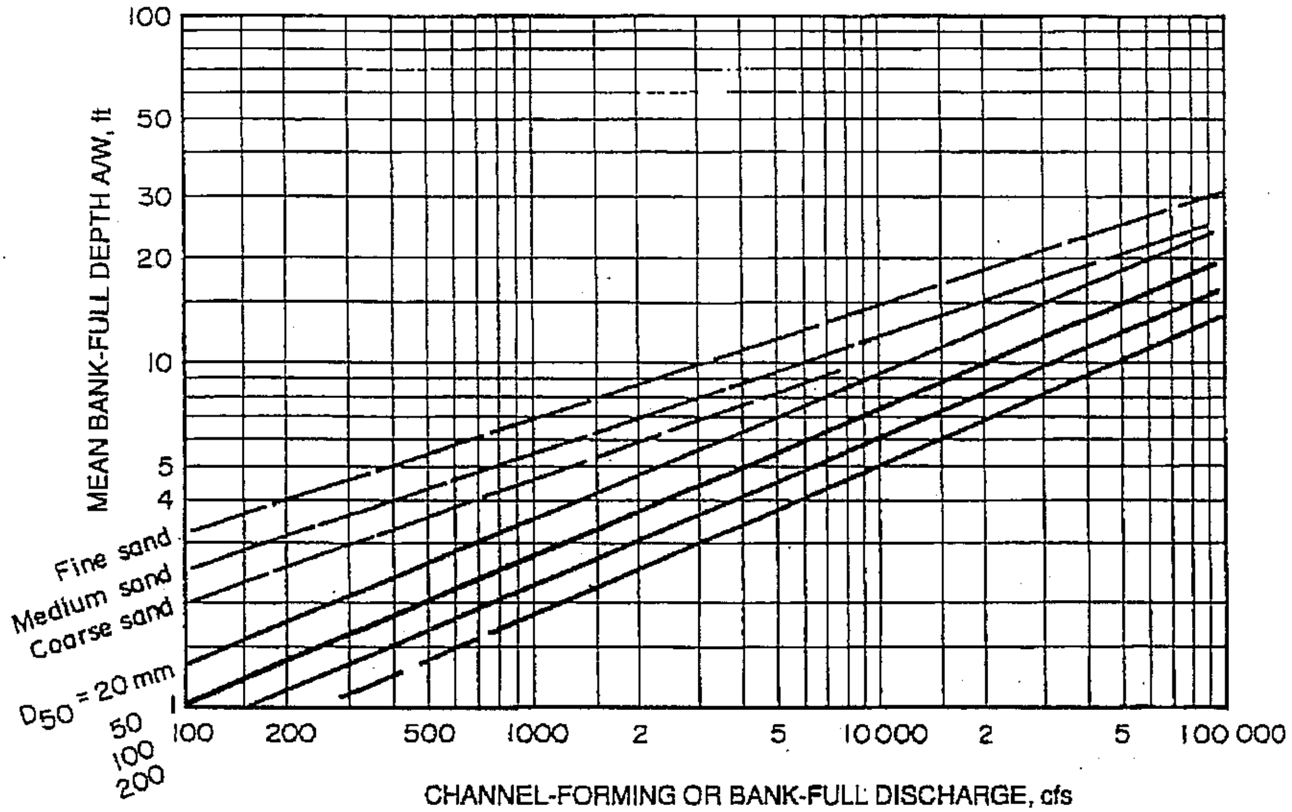


TENTATIVE GUIDANCE: CURVE 1: STIFF COHESIVE OR VERY COARSE GRANULAR BANKS.
CURVE 2: AVERAGE COHESIVE OR COARSE GRANULAR BANKS.
CURVE 3: SANDY ALLUVIAL BANKS.

SEE PARAGRAPH 5-5 FOR LIMITATIONS.

FORMULA: $W = C\,Q^{0.5}$ WITH $C = 1.6, 2.1, 2.7$

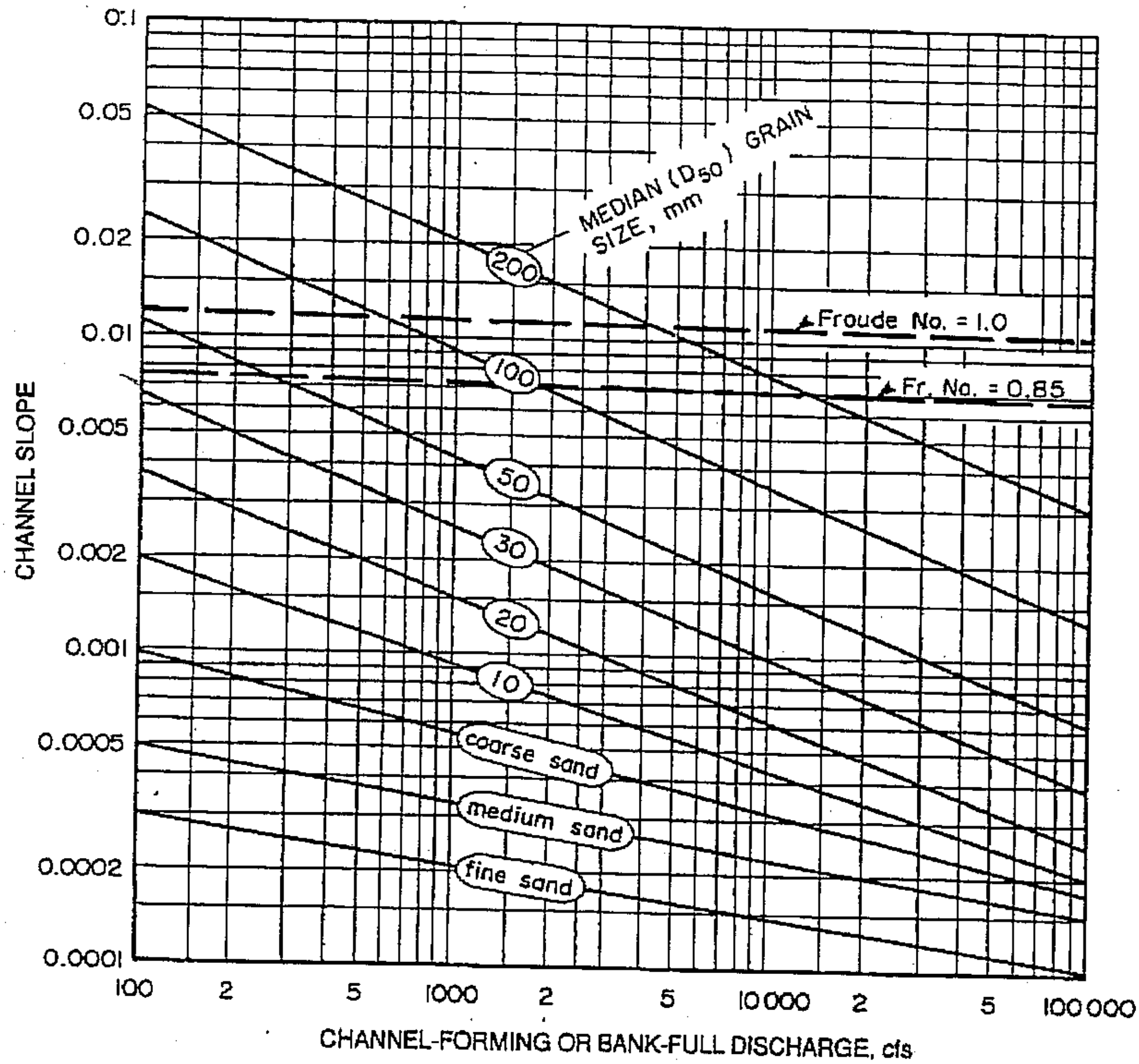
Figure 5-9. Tentative guide to width-discharge relationships for erodible channels. See Appendix B for derivation.



NOTE: FOR VERY APPROXIMATE GUIDANCE ONLY; DEPTHS SHOULD BE CHECKED BY UNIFORM-FLOW CALCULATION USING SELECTED WIDTH AND SLOPE (FIGURES 5-4 AND 5-5) AND ESTIMATED ROUGHNESS (SEE PARAGRAPH 4-7E).

APPLIES BASICALLY TO CHANNELS WITH LOW BED SEDIMENT TRANSPORT.

Figure 5-10. Tentative guide to depth-discharge relationships for erodible channels. See Appendix B for derivation.



NOTE: FOR LIMITATIONS SEE PARAGRAPH 5.5. CURVES ARE BASICALLY FOR SINGLE CHANNELS WITH FULLY ALLUVIAL BED BUT LOW BED SEDIMENT TRANSPORT. SLOPES MAY BE MUCH HIGHER WITH HIGH SEDIMENT TRANSPORT, ESPECIALLY WITH SAND BEDS.

Figure 5-11. Tentative guide to slope-discharge relationships for erodible channels. See Appendix B for derivation.